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University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

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NATIONAL UNIVERSITY OF IRELAND, CORK

Endodontic Access in All-Ceramic Dental Restorative Crown Materials

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A thesis submitted for the degree of Doctor of Philosophy (PhD)

(May, 2018)

University College Cork

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Declaration

“This is to certify that the work I am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism.”

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Catherine M. Gorman

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At the end of this very long road I would especially like to thank my supervisors Dr Frank Burke and Dr Noel Ray for their very generous advice and the unselfish giving of their time. Thank you Frank for initially giving me the opportunity to undertake this PhD, for continuously allowing me to come back to this project when circumstances got in the way of its progress time and time again, and especially for not encouraging me to give up. I would like to thank Dr Noel Ray for never losing faith in me or interest in this project when at times I couldn't see an end in sight, who was only too willing to pick up this project when I needed him and was a rock of sense at all times.

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This PhD was carried out across both dental schools in the country, I began it in the Cork University Dental School and Hospital and finished it while in the employ of the Dublin Dental University School and Hospital. I am so grateful to both hospitals for supporting me to pursue my goal and also for the support

I received from colleagues in both. A very special thank you to my recent Head of Department Dr Denise McCarthy (TCD), for her cheery kindness and interest in my career, also Dr Sharon Curtin (UCC) and Dr Martina Hayes (UCC) for their encouragement and mentorship along different stages of this PhD. I would like to thank Natalie McGettigan (TCD) for ensuring that the Dental Technology Programme continued to run smoothly whenever I was otherwise engrossed in this thesis! A big thank you to Dr Erica Donnelly-Swift (TCD) for her superb statistical support and Mr Colin Reid (TCD) for assistance with SEM.

I am grateful for the support of my sister Adrienne, who is an academic role model I could only aspire to. Also, my brothers Michael and Dermot, who amaze and inspire me on a daily basis with their 'can do' attitude to everything. My mother and late father who instilled in us the importance of education and who are the reason we're the great bunch we are! Thank you to my children who never complained when I was absent in mind and body, I wonder why that was? Kate, Kevin and Roisin you seem to have forgotten lately that I exist, well guys I've news for you, mother is back! Thanks to my friends who simply wonder what the hell I've been doing for these past few years. I've discovered that friends don't care how qualified you are, they care if you have wine! Lastly, I would particularly like to thank Ivoclar Vivadent UK, for the very generous support of materials used to conduct this research.

Glossary of Abbreviations

Abbreviation	Explanation
ANOVA	ANalysis Of VAriance
ASTM	American Society for Testing and Materials
CAD/CAM	Computer Aided Design/Computer Aided Manufacture
CBCT	Cone Beam Computerised Tomography
CNB	Chevron Notched Beam
CTE	Coefficient of Thermal Expansion
EBFS	EquiBiaxial Flexural Strength
RCT	Root Canal Treatment
FDP	Fluorescent Die Penetration
FEA	Finite Element Analysis
FE	Finite Element
FEM	Finite Element Method
FR	FRactography
GDS	General Dental Service
HF	HydroFluoric
HMOE	High Modulus of Elasticity
IF	Indentation Fracture
LD	Lithium Disilicate
LDGC	Lithium Disilicate Glass-Ceramic
LED	Light Emitting Diode
LMOE	Low Modulus Of Elasticity
MDP	Methacryloyloxydecyl Dihydrogen Phosphate
MeSH	Medical Subject Heading
MLE	Maximum Likelihood Estimate
MOR	Modulus Of Rupture
NSRCT	Non-Surgical Root Canal Treatment
NURBS	Non-Uniform Rational B-Spline
PFM	Porcelain Fused to Metal
PJC	Porcelain Jacket Crown
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analysis
RC	Resin Composite
RCT	Root Canal Treatment
SBS	Shear Bond Strength
SEM	Scanning Electron Microscopy
SEPB	Single Edge Precracked Beam
SEVNB	Single Edge V-Notched Beam
STL	STereoLithography
UVDP	Ultra Violet Die Penetration
µCT	Micro Computed Tomography

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Abstract

A diagnosis of irreversible pulpitis can occur after a crown has been permanently cemented. This necessitates the need for endodontic treatment, often with the crown *in situ*. Increasing trends indicate that all-ceramic crowns are provided as the preferred restorative option to metal-ceramic crowns. This is because modern all-ceramic restorations can now provide excellent aesthetic solutions combined with high mechanical strength properties, compared with earlier, weaker ceramic materials. It is a considerable operative challenge for the dental practitioner to prepare an endodontic access cavity *in vivo*, due to the high mechanical properties of modern dental ceramic materials. The inherent nature of ceramic materials is that they are brittle, sensitive to damage and moisture, with failure occurring in an unpredictable manner. The difficulties in performing endodontic treatment in all-ceramic crowns and subsequently repairing the access cavity is relatively unexplored in the dental literature, more research is needed to inform clinical practice in this area.

A systematic review of the literature aimed to identify influential treatment factors of endodontically accessed and repaired all-ceramic crowns and report the evidence of damage around the endodontic access cavity as a result of preparing the cavity in an all-ceramic crown. Eight studies were selected to address the aims. The inadequate volume of literature was highlighted with, the earliest relevant publication identified in 1962 and since

the last electronic search (2016) only 26 additional references were identified in the subject area. Potentially noteworthy strength controlling factors were identified to be related to the crown material, its baseline strength, the grit size of the diamond bur used to create the access cavity, the ratio of access cavity to crown dimension, the cement used to lute the crown and the presence of radial cracks after access cavity preparation.

The effect of two variables, namely, cavity dimension and modulus of elasticity of the resin composite repair material on the equibiaxial flexural strength of lithium disilicate glass-ceramic (IPS e.max® Press, Ivoclar Vivadent) material was investigated. Disc specimens with representative access cavities were used as a model system to examine these variables. Within the study limitations, the results indicate that cavity size and not the repair material, influence the equibiaxial flexural strength. The shear bond strength of the resin composite material used to repair the access cavity in a lithium disilicate glass-ceramic was determined to be comparable to those values as found in the literature (see Appendices).

Model mandibular first molar crowns were fabricated from lithium disilicate glass-ceramic to examine the impact of cavity size on failure load. The failure load for the intact crowns and crowns with a rhomboidal (based on the presence of three-canals) or rectangular (based on the presence of four-canals) endodontic access cavity, with and without a resin composite repair were measured and analysed statistically. Within the limitations, the results show that a rectangular access cavity significantly reduces the failure load which was then restored to the original values upon repair with resin composite. The preparation of a rhomboidal access cavity did not reduce the failure load compared with the intact crown.

The novel use of Finite Element Analysis (FEA) was successfully demonstrated in this subject area. Solid geometric models of lithium disilicate glass-ceramics (LDGC) crowns with three endodontic access options repaired with a resin composite (Tetric EvoCeram®, Ivoclar Vivadent) were modelled. The models were subsequently subjected to clinically relevant loads and a stress analysis was performed using FEA. This work showed that high curvature access cavity designs produced the highest stress scenario and therefore should be avoided. In an attempt to compliment the *in vitro* study computer models of LDGC discs were modelled using Finite Element (FE). The models were successfully validated, similar variables were modelled and concentric ring loading conditions were applied as per the *in vitro* study. It was determined that the size and not the stiffness of the repair material was more critical to the strength of LDGC discs.

In conclusion, this study has addressed some of the aspects of problems encountered when endodontic access cavities are prepared in all-ceramic dental crowns, however it is an area where substantial literature is lacking and therefore further research is warranted.

Chapter 1

Preface

1.1 Introduction

The presentation of irreversible pulpitis may occur after a crown has been permanently cemented, which necessitates the need for endodontic treatment, often with the crown *in situ* (Cheung *et al*., 2005). Increasing trends indicate that all-ceramic crowns provide the preferred restorative option to metal-ceramic crowns. This is because modern all-ceramic restorations can now provide excellent aesthetic solutions combined with high mechanical strength, compared with earlier, weaker materials. It is a considerable operative challenge for the dental practitioner to prepare an endodontic access cavity *in vivo*, due to the significant mechanical properties of modern dental ceramic materials. The inherent nature of ceramic materials is that they are brittle, sensitive to damage and moisture, with failure occurring in an unpredictable manner. The problem of performing endodontic treatment in an all-ceramic crown and subsequently repairing the access cavity is relatively unexplored in the dental literature.

1.2 Objectives of this thesis

The objectives of this thesis were:

1. To review the existing literature in relation to endodontically accessed all-ceramic crowns.
2. To investigate the influence of simulated endodontic access cavity size and the modulus of elasticity of resin composite repair material

on the mean equibiaxial flexural strength of representative lithium disilicate glass-ceramic (IPS e.max® Press) disc substrates *in vitro*.

3. To determine whether the geometry of the access cavity and its repair influence the mean failure load of endodontically accessed lithium disilicate glass-ceramic (IPS e.max® Press) crowns *in vitro*.
4. To construct and explore computer simulated geometric models of a lithium disilicate glass-ceramic (IPS e.max® Press) crown.
5. To virtually model selected endodontic access cavity geometries, in a lithium disilicate glass-ceramic (LDGC) crown. To apply a virtual loading scenario and conduct a stress analysis using Finite Element Analysis.

1.3 Structure of this thesis

This thesis follows the guidelines as set out by University College Cork for a Publication-Based Thesis. The thesis presents an introduction, a set of four manuscripts as thesis equivalents, two of which have been published in peer reviewed journals and two which are currently under peer review. These are followed by a general discussion and summary. Each manuscript is presented as a separate chapter. All references have been compiled at the end of the thesis. Additional supplemental material is included in the Appendices.

In Chapter Two, failure in fixed prosthodontics is discussed with particular attention given to the difficulty in defining what constitutes 'failure'. The relationship between crowns and tooth vitality, and the prevalence of endodontic intervention for fixed prostheses as reported in the literature is discussed. The factors which control strength and a discussion of *in vitro* laboratory tests, which are employed to determine the properties and performance of ceramic materials, are considered. Contemporarily available dental ceramic materials are classified and evaluated. Finally, a thorough discussion of the existing literature with respect to endodontic access of dental crowns and the technical, mechanical and biological difficulties it raises is presented.

Chapter Three is a published systematic review of the literature, which aimed to address two particular questions, namely;

1. Which treatment factors influence the fracture resistance of endodontically accessed and repaired all-ceramic crowns?
2. What is the reported evidence of damage around the endodontic access cavity as a result of preparing the cavity in an all-ceramic crown?

This systematic review facilitated thorough identification of the literature in the subject area through comprehensive search strategies. The inadequate volume of literature was highlighted, with the earliest relevant publication identified in 1962 and since then only 26 additional references were identified in the subject area. This work is published in the *Journal of Dentistry* (ISSN: 0300-5712) and addressed the first objective of the thesis.

Chapter Four investigated the effect of two variables, namely, cavity dimension and modulus of elasticity (MOE) of the repair material on equibiaxial flexural strength (EBFS) of lithium disilicate glass-ceramic (LDGC) material. Disc specimens with representative access cavities were used as a model system to examine these variables. The American Society for Testing and Materials (ASTM) standard test method was employed to measure failure load from which the EBFS was calculated (ASTM C 1499-05). The testing device was commissioned from Wyoming fixtures, USA and followed the guidelines as set out in this ASTM standard (Appendix-Section 9.6) to satisfy the chosen dimensions for the specimens in this study. This chapter addressed the second objective of the thesis and is currently submitted for peer-review.

Chapter Five addressed the third objective of the thesis. Model mandibular first molar crowns were fabricated from LDGC to examine the impact of cavity size on failure load. The failure load for the intact crowns and crowns with a rhomboidal (based on three-canals) or rectangular (based on four-canals) endodontic access cavity, with and without a resin composite were measured and statistically analysed. This chapter is currently submitted for peer-review.

Chapter Six explored the use of Finite Element Analysis (FEA) to construct and investigate predictive models of structural integrity in endodontically accessed and repaired LDGC crowns. Solid geometric models of LDGC crowns with three endodontic access options which were repaired with a resin composite (Tetric EvoCeram®) were modelled. This work is a culmination of the collaboration with the Engineering Department in UCC; Dr Denis Kelliher facilitated this endeavour and supervised Mitch Cuddihy, a postgraduate student, to carry out FEA work related to the endodontic access of LDGC crowns. The candidate (CM Gorman) worked closely with colleagues from the Engineering Department to construct the simulations from models and materials that mimicked the laboratory equivalents as accurately as possible. This work has been published in *Dental Materials* (ISSN: 0109-5641). Adjunct to this publication, this chapter also contains additional investigation of FEA models of LDGC discs with representative endodontic access cavities, both repaired and unrepaired with two different resin composites with differing moduli of elasticity, this work was explored to supplement the *in vitro* work in Chapter 4, it was not intended for publication. This Chapter addressed the fourth and fifth objective of the thesis.

Chapter Seven summarised and concluded the findings of the thesis, suggestions for further research are also outlined. Chapter Eight comprises a comprehensive compilation of references for the entire thesis. The Appendices (Chapter Nine) contain evidence of publication, a certificate of attendance at a PRISM (Promoting Research Innovation in Systematic Reviews and Meta-analyses) workshop for conducting a systematic review, evidence of a completed postgraduate module PG6001 (5 ECTS credit module) in UCC which is recorded on the candidates academic transcript, supporting statistical data and additional scanning electron micrograph (SEM) images. The Appendices also contains results of the resin composite protocol chosen in Chapter Four to repair the access cavity which measured the shear bond strength (SBS) between the resin composite and LDGC ceramic material.

1.4 Candidate's contributions to the publications

The role of the candidate and co-authors is described in this section. The candidate is the first author of the systematic review (Chapter Three) and the two manuscripts (Chapter Four and Five) that are currently under review, the candidate is second author of the FEA publication (Chapter Six) and undertook preparation of these manuscripts. The candidate undertook the study design with assistance from Dr Francis Burke and Dr Noel Ray, statistical analysis with support from Dr Noel Ray and Dr Erica Donnelly-Swift (TCD), scanning electron microscopy (SEM) with support from Mr

Colin Reid (TCD), FEA with Mitch Cuddihy and Dr Denis Kelliher (Department of Engineering, UCC). While the candidate did not directly perform the FEA modelling and analysis she worked closely with the colleagues, to provide the information for the FEA model, to design the variables addressed and with the analysis of the results. All authors contributed feedback on manuscripts prior to submission and after reviewer's comments were received. Permission has been sought by all authors for the use of published articles in this thesis.

1.5 Publications associated with this thesis

Peer reviewed papers

Cuddihy M, **Gorman CM**, Burke FM, Ray NJ, Kelliher D.
Endodontic Access Cavity Simulation in Ceramic Dental Crowns.
Dental Materials, 2013, Jun;29 (6):626-34.

Catherine M. Gorman, Noel J. Ray and Francis M. Burke
The effect of endodontic access on all-ceramic crowns: A systematic review of *in vitro* studies.
Journal of Dentistry, 2016, Volume 53C, Pages 22-29.

Catherine M. Gorman, Noel J. Ray, Erica Donnelly-Swift and Francis M. Burke
Equibaxial flexural strength determination of Lithium Disilicate glass-ceramic substrates with simulated endodontic access cavities - Impact of cavity dimension and repair material.
Under peer review

Catherine M. Gorman, Noel J. Ray, Erica Donnelly-Swift and Francis M. Burke
Effect of endodontic access cavity size and repair material on the fracture resistance of Lithium Disilicate glass-ceramic crowns: an *in vitro* study
Under peer review

Chapter 2

Literature Review

2.1 Dental crowns

Dental crowns may be used to protect and prolong the lifespan of a compromised tooth. Early attempts at crowning teeth were crude and largely unsuccessful but, nevertheless, the concept was promising. The use of gold-shell crowns to cover worn teeth were reported in the mid-eighteenth century (Hillam, 1990). In the early 1900's, casting techniques were used in dentistry to produce gold crowns, inlays and bridges (Hillam, 1990). Nowadays, crowns are widely used in dentistry with great success and can provide many years of service and prolong the life-span of the tooth. The excellent optical properties of modern dental ceramics give rise to crowns with a high level of aesthetics very similar to natural dentition (Kelly *et al.,* 1996, Clavijo *et al.,* 2016, Zarone *et al.,* 2016).

The decision to crown a tooth is usually based on at least one of the following reasons: to restore the tooth to its original shape and function where there is insufficient structure to retain a restoration, to improve aesthetics, or to provide abutments for bridges and protect the pulp. In addition, a crown can stabilise the tooth when 'cracked tooth syndrome' has been diagnosed (Mamoun and Napoletano, 2015) and protect the structural integrity of the tooth after endodontic treatment (Lynch *et al.,* 2004). Over time, for a variety of reasons, crowns may suffer from complications including failure.

2.1.1 Classification of failure in fixed prostheses

Complications with fixed restorations can be considered as failure. However, the definition of 'failure' can vary (Tan *et al.,* 2004). This makes comparison between research outcomes difficult (Conrad *et al.*, 2007). Currently, no standard exists whereby the success, survival or failure of a restoration can be accurately and universally described (Anusavice, 2012). What is considered a failure to one practitioner may equally be described as a 'complication' by another; thus making interpretation within the dental literature somewhat untenable. One study (Cheung *et al*., 2005) categorised failure of a restoration under three possible descriptions. a) biological failure of the tooth which involves caries, endodontic or periodontal disease; b) mechanical failure of the restoration which can involve loss of retention, porcelain fracture or wear, substructure (metal or ceramic) failure, fracture of an abutment tooth may also be classified as mechanical failure; and c) failure based on the quality of the restoration i.e. defective margins, poor contour or aesthetics. However, some 'failures' may be salvageable through re-intervention procedures which can prolong the survival of the crown (Burke and Lucarotti, 2009a). Re-intervention, which involves endodontic treatment under these descriptions, may therefore be described as a biological failure. The need for endodontic treatment may be classified as failure (Cheung *et al.*, 2005) and indicate the 'end of life' for a crown.

2.1.2 Retrospective analysis of *in vivo* complications in fixed prosthodontics

The clinical complications for fixed prosthodontic restorations usually relate to factors including caries, endodontic involvement, loss of retention, complete fracture, minor ceramic chipping and shade inaccuracy. Goodacre *et al.* (2003) reported that conventional bridges have a higher level (27%) of clinical complications compared with single crowns (11%) and all-ceramic crowns (8%). The authors reported complications for conventional bridges to result from caries (18%), endodontic treatment (11%) and loss of retention (7%).

Bergenholtz and Nyman (1984) identified abutment teeth to have a significantly higher rate (15%) of pulpal necrosis and periapical lesions compared with non-abutment teeth (3%). A further study reported a higher rate of pulpal necrosis for maxillary anterior teeth used as bridge abutments compared with single unit restorations (Cheung *et al*., 2005). The reason for this may be due to an overzealous attempt to parallel the preparations in order to provide a path of insertion. In one study cantilever bridges exhibited a 10% loss in abutment vitality, 8% of teeth developed secondary caries and 8% (more than half of all technical problems reported) of abutment teeth suffered from loss of retention (Hammerle *et al.*, 2000). Tan *et al*. (2004) conducted a review of the survival and complication rates of bridges after a minimum of five years which revealed pooled failure rates at a 10-year risk that the most frequent cause of biological failure was due to loss of abutment vitality (10%), caries (2.6%) and periodontitis (0.5%). The authors found that the most frequent technical complications were due to loss of retention (6.4%), material fractures (3.2%) and abutment tooth fracture (2.1%).

A meta-analysis of the survival rates between tooth supported all-ceramic and metal-ceramic single unit restorations after five years revealed that all-ceramic crowns are comparable to porcelain fused to metal (PFM) restorations (Sailer *et al*., 2015). The exceptions to this were feldspathic and silica based crowns, which were recommended to be restricted for anterior use only. The authors stated that zirconia based crowns could not be recommended as primary treatment options due to significant problems with crown delamination, chipping and retention. Despite extensive research into the problem of delamination in zirconia dental restorations it continues to be reported as a major complication for this restorative material (Section 2.4.3). Goodacre *et al.* (2003) found the incidence of clinical complications of dental crowns over a 50-year period to have a 3% (2.7-6%) incidence of porcelain fracture (n=199), 2% (1-23%) loss of retention (n=1061), 0.6% periodontal disease (n=986) and 0.4% caries involvement (n=1105). The authors combined the findings of five studies (Lundqvist and Nilson, 1982, Cheung, 1991, Jackson *et al.,* 1992, Milleding *et al.,* 1998, Walton, 1999) to report a 3% (0-6%) incidence of endodontic treatment for 27 out of 823 dental crowns.

Burke and Lucarotti (2009b) conducted a retrospective analysis of 47,474 crowned teeth in the National Health Service General Dental Service (GDS) in England and Wales over a ten-year period (1991-2001). The authors analysed data for 10,426 crowned teeth which required some form of re-intervention. Of this number, endodontic treatment accounted for 12% of re-interventions which equated to 2.6% (1,251 of 47,474) of the data overall. Similary, Pjetursson *et al.* (2007) reported a 2.1% incidence of loss of vitality from a meta-analysis of 34 studies within a 5-year period for all-ceramic crowns. More recently studies reported in the literature highlighted rates of re-intervention for all-ceramic crowns requiring endodontic treatment of 4% (9 of 205), 2.5% (34 of 1335) and 8.6% (19 of 219) for 5 year (Ortorp *et al.,* 2012), 8.5 year (Beier *et al.,* 2012) and 7 year (Rinke *et al.,* 2015) follow-up intervals. Another UK study has reported much higher incidences of pulpal complications compared with these studies (Saunders and Saunders, 1998). The authors reported a high incidence (19%) of periradicular disease in 87 of 458 crowned teeth when assessed radiographically, thus highlighting the asymptomatic potential for pulpal complications which may therefore go under-recorded. Furthermore, higher incidences of periapical radiolucent lesions have been determined when cone beam computer tomography (CBCT) imaging was employed compared with traditional periapical radiographs (Cheung *et al.,* 2013). CBCT imaging was found to be a significantly more effective tool compared with periapical radiographs to determine the presence and number of roots and canals and periapical radiolucent lesions in posterior teeth (Cheung *et al.,* 2013).

2.1.3 The relationship between crowns and tooth vitality

The literature clearly shows endodontic involvement to be a significant clinical complication from restorative dental treatment. Pulpal necrosis may occur as the ability of the pulp to recover from restorative treatments may be difficult when repeat restorations become increasingly larger, a phenomenon known as the Repeat Restoration Cycle (Elderton, 2003). The decision to place a crown is often made after the maintenance of the existing tooth in its current condition becomes no longer viable. However, preparation of the tooth in order to receive such a restoration can result in additional irritation to the pulp. Abou-Rass (1982) aptly coined the phrase 'stressed pulp'. The cause of damage to the dentine-pulp complex can be multi factorial and is most likely a result of the chronological cumulative effect of caries, caries removal and finally, crown preparation (Fouad and Levin, 2011). Each successive physical insult reduces the capacity of the pulp to recover and remain vital. Crown preparation is irreversibly destructive to tooth tissue, for example, the preparation of anterior all-ceramic crowns typically necessitates the removal of 62-73% of tooth structure (Edelhoff and Sorenson, 2002). The link between tooth destruction, along with the cumulative stages of dental crown fabrication and possible pulpal complications is well documented in the dental literature (Dahl 1977, Bergenholtz 1991, Jackson *et al.,* 1992, Goodacre and Spolnik 1994, Christensen 1997, Christensen 2005). The remaining dentine thickness over the pulp is of particular importance, as this is reduced, so too is the capacity of the pulp to tolerate noxious stimuli from restorative materials that can induce an inflammatory response (Hilton, 2009). Some irritants which can impact the ability of the pulp to remain vital include the material to which it is in proximity, such as dental amalgam (heat conductor) or resin composite (irritant), enamel/dentine primer (opens dentine tubules which can result in incomplete polymerisation of the resin due to the increased presence of fluid, thereby irritating the pulp). Other irritants include heat build-up from pressure and speed during the preparation procedure, temperature rise from some light curing devices with high-energy outputs (Hannig and Bott, 1999). Kirakozova and Caplan (2006) determined that age and extensive preoperative tooth reduction were important predictors of subsequent pulpal involvement in crowned teeth. Due to the large pulp chamber and thin dentine layer found in younger teeth, this risk factor decreased with increased age due to the presence of a thicker dentine layer. Extensive preoperative tooth destruction was associated with poor pulpal protection particularly when the root surface was involved, this was correlated with the reduced tertiary dentine production in older patients which therefore provided less pulpal protection.

2.2 Endodontics

2.2.1 Endodontic options for teeth restored with a fixed prostheses

Where the pulp is exhibiting signs of pathology under an existing restoration the options are to carry out endodontic treatment or extract the tooth. Endodontic access of teeth restored with a fixed prosthesis can be achieved in one of three ways. Firstly, the crown may be removed in order to access the root canal system. This may be an appropriate option when other shortcomings of the existing crown are evident, such as unsatisfactory colour match and poor marginal integrity. It is also impossible to visualise the pulp chamber radiographically with the crown *in situ*. Occasionally, it may be possible to recover a crown intact with a subsequent re-cementation, which will evidently be more difficult if it is bonded with a resin-based luting material. The advantage of crown removal is that it permits assessment of the condition of the underlying tooth substance and its restorability (Manogue *et al*., 2005). Also, location of the pulp canal chamber is easier. Disadvantages are that isolation of the tooth with a rubber dam is more difficult if the crown is removed and the additional cost of replacement should the crown fracture during removal.

Secondly, the crown may be perforated (Figure 2.1) in order to gain endodontic access and the access cavity is subsequently repaired (Schwartz and Fransman, 2005). This may be the preferred option due to financial implications particularly if the crown has recently been placed and/or adhesively cemented. For PFMs this technique is relatively straightforward (Schwartz and Fransman, 2005) but it carries more elements of risk for all-ceramic crowns (Michanowicz and Michanowicz, 1962, Davis, 1998). The difficulties with high-strength ceramic materials include cutting and subsequent removal of the restoration especially if the restoration is bonded to tooth structure. When a tooth is already crowned, the canals may not be in the location expected once access is gained (Figure 2.2 a)) due to morphological differences between the crown and the original tooth (Figure 2.2 b)). This can necessitate the access cavity dimensions to be extended beyond the minimum requirement.

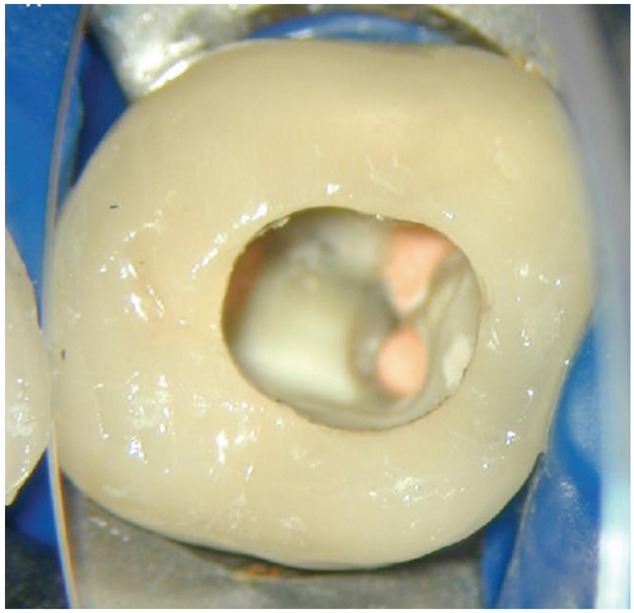

Figure 2.1 An endodontic access cavity which has been prepared through a metal-ceramic crown, note the obturated root canals, the cavity must now be filled with a restorative material to restore the missing tooth structure, occluding surface and contour of the crown (Schwartz and Fransman, 2005).

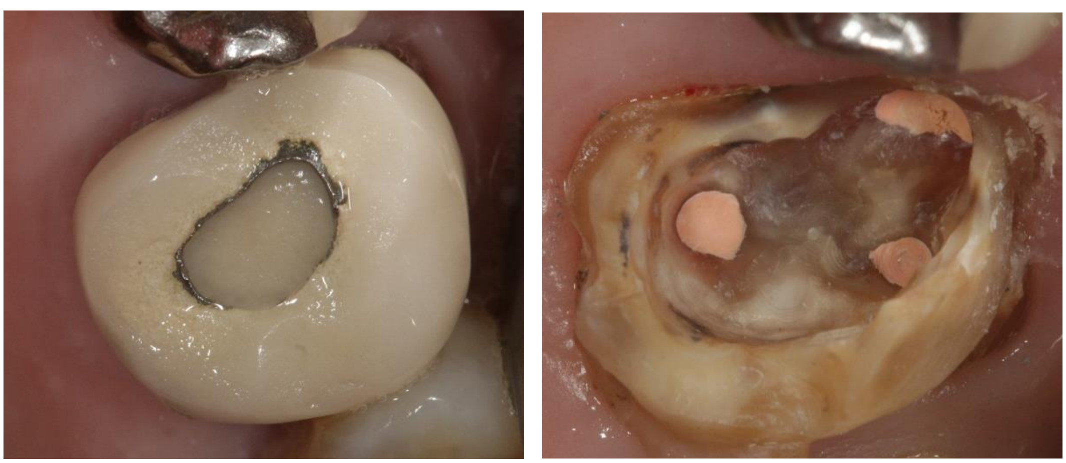

Figure 2.2. a) An endodontic access cavity prepared through a PFM crown on a maxillary left first molar, the root canal positions were difficult to identify due to their unexpected mesial location which would have necessitated excessive enlargement of the access cavity in the crown. b) the crown was subsequently removed to permit access to the root canals. (Photo courtesy of Dr David McReynolds, TCD).

Thirdly, endodontic access can be made using a retrograde approach which involves the apical surgery of the root in question. The advantage of this is that the crown remains intact and any complications associated with its perforation are avoided. This is an extreme solution to the problem and is not without its disadvantages namely, its technical feasibility. It has also been associated with gingival recession and visual scarring of the soft tissue around the tooth in question (Jonasson *et al*., 2008).

Finally, if none of the above solutions satisfy, an alternative option would be extraction of the tooth and possible provision of a prosthesis (fixed, removable or implant retained). Endodontic treatment should not be initially bypassed in favour of implant treatment as there are biological and financial advantages to retaining the natural tooth (Iqbal and Kim, 2008). However greater outcome predictability may be possible with implants (Thomas and Beagle, 2006). The dilemma exists for dental practitioners whether to prolong treatment of a badly damaged tooth or extract the tooth and replace it with an implant (Dawson and Cardaci, 2006). Comparisons between the success rates of either endodontic or implant treatment are difficult to make due to the very different criteria employed to measure their success.

2.2.2 Root canal morphology of permanent dentition

Endodontic access openings are primarily configured based on the anatomy and pulp chamber morphology for each individual tooth.

Initially an outline form for the access cavity assists in locating the correct pulp chamber and canal position and creating the correct shape required to ensure straight line access to the canals. Subsequently the access cavity can be modified further for convenience in locating additional canals and to permit canal instrumentation (Johnson and Williamson, 2015). Straight line access facilitates complete debridement of the root canal which is essential for a successful endodontic outcome, this also reduces the risk of instrument fracture. The definitive access design will depend not only on the orifice location but also on the position and curvature of the entire canal.

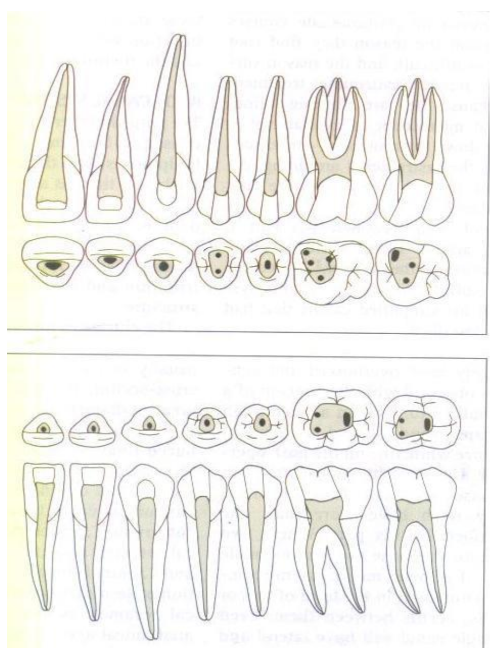

Figure 2.3 Classic endodontic access openings based on typical number of roots and canals for individual tooth types (Carrotte, 2011).

While generally standardised access opening designs apply for individual tooth types (Figure 2.3), customisation is usually necessary to accommodate individual cases especially for posterior teeth. Posterior teeth have a higher percentage of root and canal aberrations compared with anterior teeth (Gutman and Fan, 2015). The mandibular first molar has normal recurring features with a number of atypias (Maggiore *et al.,* 1998). The usual configuration for the mandibular first molar is two canals in the mesial root, although three are possible (Vertucci, 1984) and one canal in the distal root, which will result in an approximately triangular or rhomboidal endodontic outline access form (Figure 2.4 a)). In approximately one third of cases, a second canal is present in the distal root (Skidmore and Bjorndal, 1971 and Hartwell and Bellizzi, 1982) necessitating a more rectangular outline access opening form (Figure 2.4 b)). Considerable variation in root canal morphology is found amongst various ethnic population groups. Variation in root canal morphology also changes with the progression of age (Peiris *et al.,* 2008). A larger access cavity outline form may also be recommended for a geriatric or medically compromised patient to facilitate ease of access and speed of treatment.

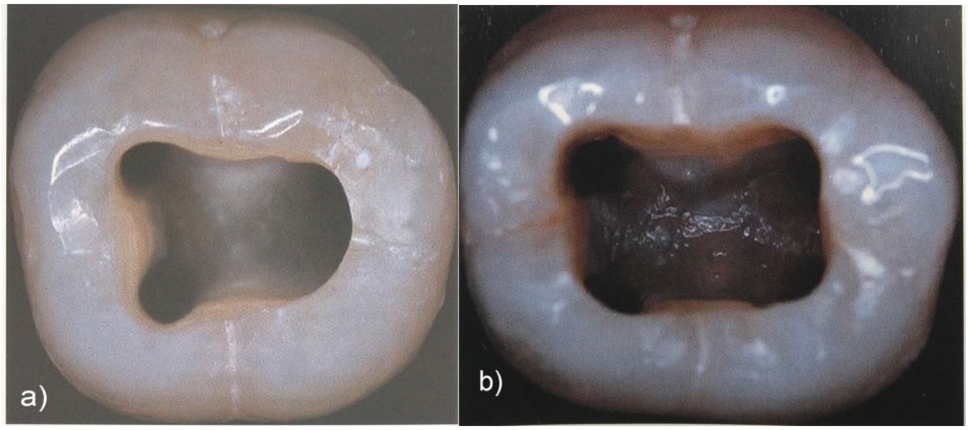

Figure 2.4 Endodontic access openings based on the presence of a) three-canals and b) less common four-canals for a mandibular first molar tooth (Johnson and Williamson, 2015).

2.2.3 Standard root canal preparation

Root canal preparation involves the removal of pulpal tissue, and the subsequent cleaning and filling of the canal. This procedure is carried out in a step by step fashion (Manogue *et al*., 2005).

1) An access cavity is prepared, the purpose of which is to remove the roof of the pulp chamber to gain access to the pulp chamber and root canal orifice(s).
2) The identification of the canal orifices can be achieved once the pulp chamber has been thoroughly cleaned.
3) Tentative exploration of the canal is carried out to ensure that it is negotiable. Once this has been achieved coronal flaring is advised, which involves tapering up to half of the root canal coronally thus

allowing full negotiation of the canal and the working length of the canal can therefore be determined.

4) Apical canal preparation involves apical enlargement and tapering via the careful manipulation of selected files.
5) Debris is flushed out using an anti-bacterial irrigating solution such as sodium hypochlorite. An intracanal medicament may be placed which serves two purposes, firstly it reduces the bacterial re-population in the canal and it secondly offers protection from microleakage between appointments.
6) Obturation is carried out to provide a "dense, homogeneous, three-dimensionally filled root canal" (Manogue *et al*., 2005). This procedure should offer protection from further ingress of microorganisms. An apical seal is achieved via the obturation process.
7) A coronal seal is achieved by placing a 2-3mm layer of glass ionomer cement (or similar) over the root canal orifices and the pulpal floor.
8) A final restoration is placed and depending on the degree of restoration required, this can vary from a simple resin composite filling to a complete crown. The placement of a complete crown is often the treatment of choice where a tooth is badly decayed and broken down. The success of endodontically treated teeth has been shown to be influenced by the restoration type, with the placement of permanent coronal restorations being associated with a higher survival rate (Lynch *et al.*, 2004).

Care must be taken not to contaminate the exposed ceramic surface for bonding the adhesive access cavity repair if eugenol-based materials have been used in the obturation procedures (Davis, 1998). The success of root canal treatment relies on thorough execution of the above procedure. In particular, repopulation of bacteria in the canal must be prevented, as this has the potential to occur quickly and can lead to infection of the tooth, which would require endodontic retreatment, or extraction of the tooth (Schwartz and Fransman, 2005).

2.2.4 Endodontic access in teeth restored with fixed prostheses

Estimates suggest that 20-50% of non-surgical root canal treatment (NSRCT) is performed through dental crowns (Goldman *et al*., 1992). A survey (Trautmann *et al.,* 2000a) of 543 dental practitioners (endodontists, prosthodontists and general practitioners), highlighted that 72% choose to gain access to the pulp chamber through existing crowns and maintain it as a permanent restoration, rather than remove the crown (17%) or place a temporary crown (11%). The same survey revealed that 36% of practitioners reported the age of the crown when NSRCT was required, to be < 5 years, 52% between 5 and 10 years and 13% > 10 years (Trautmann *et al.,* 2000a).

Many aspects must be considered when deciding to repair an endodontic access cavity if the restoration is to be considered definitive. Most general practitioners, endodontists and prosthodontists usually carry out the restoration of the access cavity after the NSRCT of crowned teeth (Trautmann *et al*., 2000b). Amalgam or bonded amalgam was reported to be the material of choice for restorations through full metal crowns and resin composite was the choice material for ceramic crowns. Schwartz and Fransman (2005) conducted a review of the available restorative materials for access cavity repair in metal-ceramic and all-ceramic crowns. One of two methods of access cavity restoration in teeth with all-ceramic restorations were advised; the incremental build up and light curing of resin composite or, for speed, bulk filling with a glass ionomer cement and veneering with a resin composite material.

2.3 Strength characteristics of dental ceramic materials

Ceramics are brittle linear elastic materials which lend themselves favourably to dentistry as long-term restorative materials. Their attractiveness lies in the fact that they can be readily configured to mimic the colour and form of natural dentition both manually and using Computer Aided Design/Computer Aided Machining (CAD/CAM) techniques. Improvements in the mechanical properties of ceramic materials over recent decades have permitted wider applications of ceramics in the oral environment. As a result, traditional PFM restorations are now frequently bypassed for all-ceramic alternatives (Christensen, 2011). Ceramic restorations are however, generally limited to single units or short span bridges due to relatively lower tensile strength and fracture toughness compared to metal-ceramic bridges.

The mechanical failure of dental ceramic materials both *in vivo* and *in vitro* remains a ‘murky’ area, despite extensive research which has been carried out over decades. Ideally, testing the strength of a material should involve test procedures as they relate to the end use of the data for component design, quality assurance and service life (Kelly, 1995, Cranmer and Richerson, 1998, Freiman and Mecholsky, 2012). Data derived from testing ceramics should be error free (Quinn and Quinn, 2010) and, in order to achieve this, the testing variables must be tightly controlled. Reported statistical variance in the testing of dental ceramics place a stringent requirement on the minimum number of specimens to ensure relatively accurate values are obtained (Freiman and Mecholsky, 2012).

Randomised controlled trials, are considered the ‘gold standard’ method of evaluation for dental materials and procedures. However, while they are desirable, long-term randomised controlled trials are frequently impracticable due to the length of time taken from inception to conclusion and application of results. Materials and techniques in dentistry evolve at a fast pace and this makes *in vitro* tests a realistic option for assessing the suitability of materials for clinical use within a reasonable time-frame. Frequently, inter-laboratory results often have wide variances due to non-standardised testing regimes. ‘Round robins’ (Interlaboratory comparative studies) are one method of improving this problem but are expensive and difficult to organise (Quinn, 2015). *In vitro* simulations fall short in duplicating intra-oral biological events but rather *in vitro* testing is useful for ‘ranking’ a materials suitability for clinical use. In addition, the use of FEA has a potential role to play in predicting the performance of dental materials and is discussed in Section 2.3.4.

Ceramics can withstand high compressive forces, but their major drawback relates to flaw sensitivity (i.e. low fracture toughness), the severity and the location of which determine the strength of a component particularly with respect to tensile stress (Freiman and Mecholsky, 2012). Ceramic materials do not have the ability to deform plastically and thus failure occurs in a catastrophic manner and without prior warning. The flaw sensitivity of ceramics is compounded by their behaviour in moisture which enhances slow or subcritical crack growth (SCG). SCG is a phenomenona whereby the strained bonds at the crack tip readily react with moisture in order to relieve stress. If the environment (stress and moisture) continues, the crack length will grow to a critical length when failure will occur (Freiman and Mecholsky, 2012). The oral cavity is an extremely harsh environment where ceramic restorations are required to perform in function, are constantly bathed in saliva, and subjected to masticatory forces as a matter of routine. SCG in dental ceramic restorations can lead to time-dependent strength degradation (Gonzaga *et al.,* 2011).

2.3.1 Fracture toughness

Fracture toughness (K_{Ic}, MPa $m^{0.5}$) is defined as a measure of the ability of a material to resist fracture in the presence of a crack (Passos *et al*., 2015). The strength of a ceramic is determined by its fracture toughness and by the length of the microcracks it contains. While a material with a high fracture toughness is desirable, this does not always translate into higher strength since the fracture toughness is also the effect of crack size-to-grain size ratio (Freiman and Mecholsky, 2012). Fracture toughness data is useful in ranking materials for selection, it is not used for the prediction of strength or reliability. If the longest microcrack in a given specimen has length 2a, and K_{1C} is equal to the fracture toughness, then the tensile strength (σ) is given by Griffith's equation (Ashby and Jones, 1988).

$$\sigma = \frac{K_{1C}}{\sqrt{\pi a}}$$

The equation shows that there are two ways of improving the strength of ceramics, by decreasing the microcrack length (with careful quality control) and by increasing the fracture toughness.

Fracture toughness can be measured using several methods, namely, indentation fracture (IF) technique, single edge v-notched beam (SEVNB), fractography (FR), single edge precracked beam (SEPB) and Chevron notched beam (CNB) (Passos *et al.,* 2015). The SEPB and CNB methods are reliable methods of testing fracture toughness compared with indentation methods which are more prone to the effects of SCG. Indentation fracture methods are popular but have limitations in that the crack length may be overestimated due to the effects of SCG thus giving artificially higher values for fracture toughness. Immediate post-indentation measurement is therefore essential to minimise this effect. Although IF is more widely used due to technique simplicity, values cannot be reliably used to compare data from different studies (Passos *et al.,* 2015). For example, a wide range of fracture toughness values are reported for Y-TZP ceramic, the observed differences were proposed to be attributed to, different processing methods, material formulations, methods used to calculate fracture toughness and study designs (Passos *et al.,* 2015).

The microstructure of ceramic materials is an explicitly critical factor in defining the resistance to fracture (Freiman and Mecholsky, 2012). Small defects (such as cracks and pores) are typically present as a result of processing and machining ceramics for their intended use. Sintered products are not fully dense, they generally contain pores which weaken the material particularly if they are sharp and angular. Thermal stresses caused by cooling or thermal cycling can generate small cracks. Cracks are more damaging than pores and are often present as a result of processing, or initiated by differences in thermal expansion between phase differences e.g. glass matrix and crystalline phases. A sharp crack induces an area of higher stress concentration which will cause the crack to grow to a critical size when failure will occur. Processing methods aim to reduce the size and number of cracks and pores, yielding ceramic bodies with higher tensile strengths. Ultimately, dental ceramics are brittle materials and their strength is controlled by the presence of defects, typically the largest defect in the area of greatest stress will determine the primary source of failure (Thompson *et al*., 1994). This is further complicated on a long-term basis due to the requirement of ceramics to perform in a moist environment and the inherent problem of static fatigue.

The microstructure can affect fracture in many ways including increasing the materials crack resistance via crack deflection, the more tortuous the path of the growing crack the higher the fracture toughness, grain size and grain orientation influence this effect. Generally, dental porcelain has a high glass content and corresponds to lower fracture toughness but particle dispersion (eg “aluminous porcelain”) can deflect cracks to increase the fracture toughness. In addition, a coefficient of thermal expansion (CTE) mismatch between the glass matrix and ceramic particles can induce compressive stress, which may strengthen the material. Materials with an interlocking microstructure such as LDGC (Figure 2.8) impart a high fracture toughness to a material due to the high aspect ratio of the acicular crystals, which promote crack bridging. Phase transformation is another mechanism of toughening ceramics, the most known example of this is partially stabilized zirconia (ZrO_2) where the tetragonal phase is partially stable due to the addition of yttrium (Y_2O_3). When the material undergoes stress it transforms to a more stable monoclinic structure. The result of which is to produce compressive stresses in the area around the crack tip which partially shield the crack tip from the high stress intensity, thereby increasing its toughness. Further discussion of zirconia ceramic materials is found in Section 2.4.3.

The characterisation of the mechanical strength of ceramic materials for dental applications involves assessment of physical properties of which, fracture toughness, flexural strength and hardness are the most frequently reported. The mechanical properties of some currently popular dental ceramic materials are presented in Table 2.1.

2.3.2 Flexural strength

Flexural strength (MPa), also known as the modulus of rupture (MOR) or bend strength, is a mechanical parameter for a brittle material, which is defined as a materials ability to resist deformation under load (ASTM F 394-78). Some factors which influence the apparent strength of a material are listed below and discussed further, combinations of these factors serve to further increase the complexity of a given stress state.

1) The shape of the specimen i.e. disc or bar, the dimensions of which also relate to the strength values recorded due to the phenomena of strength-scaling (Kelly, 1995).
2) The surface condition of the specimen (Kelly, 1995), such as air-abraded, etched, glazed or resin coated. Also, surface finish can give rise to friction between the specimen and fixture (Giordano *et al.,* 1995).
3) The loading parameters, applied load, rate of loading, contact stresses, loading piston (ram, ball, ring) used. Atmospheric conditions, i.e. humidity, test conditions wet or dry, thermocycled, thermomechanical loading, dynamic loading.
4) The microstructure of ceramics, this can also be influenced by processing parameters which ultimately control the flaw size, shape and location which in turn determine strength.
5) Different analytical solutions which can be used to calculate values for flexural strength by Timoshenko, Shetty and Roark (Kelly, 1995).

2.3.2.1 Specimen dimension

In vitro test methods which are employed to measure the flexural strength of ceramic materials include, uniaxial (three-point bend, four-point bend) flexure testing (Figure 2.5 and Figure 2.6) using bar-shaped specimens and biaxial flexure tests (Figure 2.7) using disc-shaped specimens (Kelly, 1995, Morrell, 2007). All are well-established techniques for the determination of brittle material flexural strength. One of the main disadvantages of the three-point or four-point bend test is that fracture is often initiated from the edges of the specimen, these are considered spurious failures and the measurements recorded invalid. Shorter specimens which are required for three-point bend testing typically produce higher flexural strengths than those specimens tested with a higher length to support ratio (four-point bend) (Kelly, 1995). The reason for his has been explained through the phenomena of strength-scaling (Quinn and Quinn, 2010). Smaller specimens will statistically contain fewer flaws (assuming homogenous flaw distribution). In structural engineering, scaled down dimensions of specimens are frequently tested when it is impractical to test larger specimens. However, larger specimens will contain a greater number of flaws and statistically the probability of failure from one of these flaws is increased, this results in lower strength values reported for larger specimens compared with smaller specimens of the same material. Therefore, extrapolation of strength data to larger and more realistic requirements may not be considered good practice (Cranmer and Richerson, 1998, Quinn and Quinn, 2010).

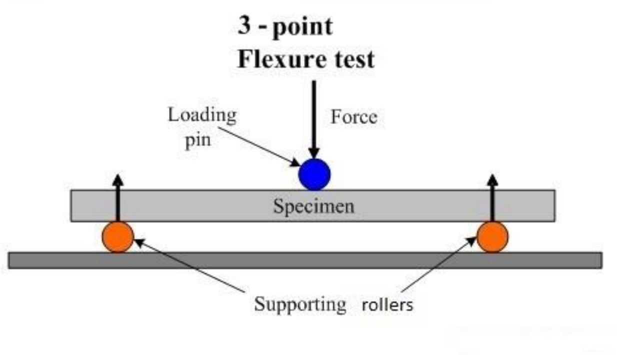

Figure 2.5 Schematic representation of the basic fixture and test specimen for 3-point uniaxial testing using a centrally loaded bar-shaped specimen (ASTM F 394-78).
(http://www.substech.com/dokuwiki/doku.php?id=flexural_strength_tests_of_ceramics Date accessed 15/3/18)

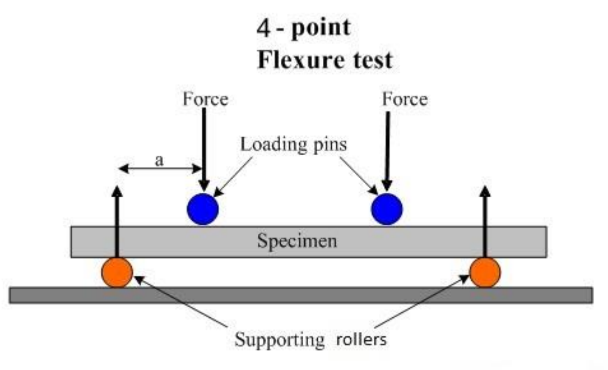

Figure 2.6 Schematic representation of the basic fixture and test specimen for uniaxial testing for a 4-point flexural test (ASTM C1161).
(http://www.substech.com/dokuwiki/doku.php?id=flexural_strength_tests_of_ceramics Date accessed 15/3/18)

The biaxial flexure test is an alternative to three-point and four-point bend tests. In order to carry out this test, flat plate (disc or square) specimens are required. The stress induced in dental crowns during function is biaxial in nature, for this reason the biaxial flexural test is popular and suited for the purpose of determining strength (Hsueh and Kelly, 2009). It is an especially useful test because, the edges of the specimen are not stressed, therefore spurious edge fractures are significantly reduced and more consistent results can be produced. Also, the surface to volume ratio may be considered more representative of a dental crown compared with a bar-shaped specimen (Piddock *et al.*, 1987). A number of corrections are available for the stiffening effect of the material which overhangs the support circle, however, its effect on the measurements obtained are considered negligible (Kelly, 1995), this being so, square-shaped specimens can be readily accommodated. Variations in test fixtures for the biaxial test include, piston-on-ring, piston-on-three-ball, ball-on-ring, ring-on-ring (Hsueh and Kelly, 2009).

Each test fixture is associated with its own advantages and disadvantages which may favour, or not, specimen geometry, frictional effects, alignment in the test jig and analytical solutions. The ‘ring-on-ring’ method (ASTM C 1499-05, for testing the monotonic equibiaxial flexural strength of advanced ceramics at ambient temperature) uses concentric support and load rings which permit the testing of disc specimens (Figure 2.7). One stipulation of this test is that the specimens must be flat to within 0.1 mm in 25 mm. Specimens can be relatively easy to make and are tested within a short space of time. It is the simplest form of loading and may be considered analogous to the four-point bend test (Morrell, 2007). This testing fixture ‘uniquely’ facilitated the testing of flexural strength in the current study (Chapter 4). The ceramic disc specimens had a representative endodontic access cavity trephined in the centre and no other test method available could satisfy the requirement for flexural testing with specimens of this geometry.

Flexural strength values for IPS e.max® Press between 239 and 466 MPa were reported (Table 2.1), different test methodologies were used for the measurement of these values (Ivoclar Vivadent, 2011). The large variation, were a result of, 3-point uniaxial, 4-point uniaxial and biaxial tests, some values reported included studies where flexural strength was measured in water.

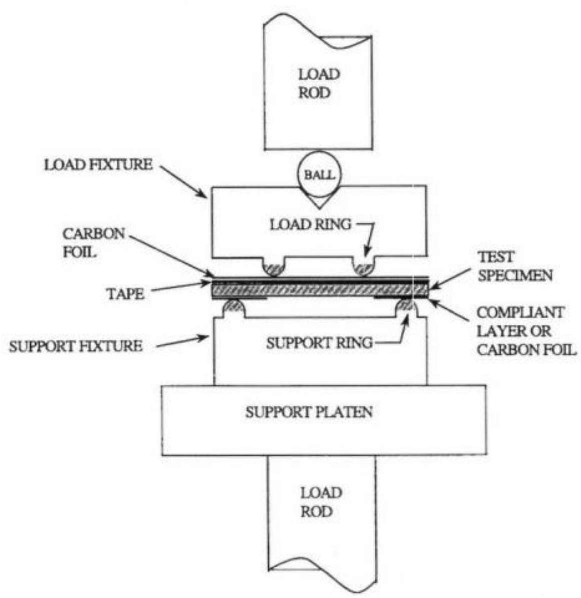

Figure 2.7 Schematic representation of the basic fixture and test specimen for EBFS testing using a ring-on-ring method (ASTM C 1499-05).

2.3.2.2 Surface condition

Strength has been clearly linked to the extrinsic surface condition of a material (Kelly, 1995, Giordano *et al.,* 1995, Albakry *et al.,* 2004). The adjustment of ceramic restorations is frequently carried out in the laboratory or chairside to improve fit, contour or occlusal contacts (Song and Yin, 2009). This can introduce surface and subsurface damage which may lead to the ultimate failure of the material. Machine-induced damage can be minimised by carefully controlling the rate and depth of material removal (Song and Yin, 2009, Song *et al.,* 2016). It was established that LDGC was significantly ($p<0.05$) more difficult to machine compared with leucite glass-ceramic, and that feldspathic glass-ceramic was the least difficult to machine compared with both materials (Song *et al*., 2016). LDGC (IPS e.max® CAD) was ranked the least damage tolerant ceramic material and resulted in flexural strength reductions up to 63% depending on the grit size of the grinding tool that was employed to perform adjustments (Coldea *et al*., 2015). A sequential approach from coarse to fine-grit instrumentation was consequently recommended by the authors.

Glass-ceramic materials are typically etched prior to cementation, this process increases the surface area for bonding. The application of a resin composite layer has been shown to positively influence the fracture strength (Burke *et al*., 2002). This is discussed in further detail in Section 2.4.4.

2.3.2.3 Load parameters

Differences in the geometry of the load and support devices can vary widely between studies. The geometry of the loading piston can affect material failure (Yi and Kelly, 2008). Yi and Kelly (2008) highlighted the similarity of the contact between a flat piston and ceramic and that of wear facets found intraorally. The authors suggested that the effect of edge-loading may be overcome with the introduction of a thin plastic layer between the piston and ceramic and with the use of a piston with low elastic modulus. Small spherical indenters were found to produce artificially high stresses, inducing surface damage and failure mechanisms unrepresentative of a clinical scenario. The clinical failure of restorations typically occur from the internal surface (Kelly, 1999). Spherical indenters with a larger radius are deemed to produce more clinically relevant crack patterns (Kelly, 1999, Kelly *et al*., 2010). In addition, load rates which ensure the fast fracture of specimens (10-15 sec) should ideally be employed to prevent the effects of SCG (ASTM standard C1499-05).

2.3.2.4 Analytical solutions

The stress analysis for biaxial flexural tests is complex and different formulae have been derived for the calculation of the biaxial flexural strength of ceramic materials (Kelly, 1995, Hsueh and Kelly, 2009). The formulae used to calculate values for flexural strength are based on those developed by, Timoshenko, Shetty, Roark (Kelly, 1995). The investigation in Chapter

4 employed the widely used Timoshenko equation as set out in the ASTM standard C1499-05.

2.3.3 *In vitro* testing of failure load of crowns simulating the clinical scenario

The fracture resistance of all-ceramic crown restorations is frequently reported in terms of failure load values. Testing ceramic materials using complete contour crowns subjected to monotonic loading which induces a compressive state of stress is frequently employed to measure a materials resistance to fracture. This is not a property of the materials, *per se*, but rather a combination of the factors under which the test has been set up. Mean maximum masticatory forces in humans are reported to be in the range of approximately 600 to 900 N for female and male subjects, respectively (Cosme *et al.,* 2005, Varga *et al.,* 2011). A maximum bite force of 738 ± 209 N (Braun *et al.,* 1995) was recorded in the molar region. To promote failure loads within a normal functional range and fracture patterns analogous to the clinical scenario it is recommended that load spheres with a large diameter should be used (50 mm), loading should be cyclic and in an aqueous environment, fast fracture is also essential to avoiding problems with SCG (Harvey and Kelly, 1996). Generally, values obtained are restricted to comparisons within the study and not across studies due to the inhomogeneity of study designs.

The failure load is influenced by the MOE of the core to which it is cemented (Scherrer and DeRjik, 1993, Lee and Wilson, 2000). A core material with a higher MOE has been shown to yield higher failure loads. Lee and Wilson (2000) determined that the failure loads of aluminous porcelain jacket crowns (PJC's) were, 600 ± 95 N, 670 ± 134 N, 682 ± 138 N and 873 ± 96 N when luted to brass, gold alloy, titanium and cobalt chromium die materials, respectively. The elastic modulus of the die materials were 100 GPa, 113 GPa, 117 GPa and 218 GPa, respectively. The cement thickness and bonding status are other important variables controlling failure loads (May *et al.,* 2012). These authors compared laboratory models of feldspathic crowns (Vita Mark II blocks) with FEA models, and found that for both methods an increased cement space caused a decrease in failure load. Crowns which were bonded could withstand higher loads compared with non-bonded crowns, this 'bonding' effect was gradually diminished with increased cement space, thus emphasising the importance of excellent internal crown fit and complete seating on cementation.

2.3.3.1 Fractographic analysis

Fractographic analysis of failed dental crown specimens is a valuable technique but is not widely used in dentistry. Fractographical examination can be employed to determine the fracture origin and failure pattern of a ceramic specimen or crown. It is possible to calculate fracture toughness and strength values from the fracture process which is recorded through regions around the critical flaw and are known as mirror, mist and hackle markers (Thompson *et al.,* 1994). Thompson *et al*. (1994) determined that fracture initiation sites in all-ceramic crowns (Dicor and Cerestore) were initially controlled by the location and size of the primary flaw and that the ceramic thickness plays a secondary role. Retrieved clinical crown failures analysed using fractography highlighted the importance of hoop stress and failure from the margin of crowns (Quinn *et al.*, 2005). Fracture origins were located at or within the core material. Nasrin *et al*. (2016) concluded that bonded model glass restorations experienced highest stress in the wall and margin areas of the crown.

2.3.4 Finite Element Analysis (FEA)

No single *in vitro* laboratory test can be used to predict clinical performance, however an increase in the predictive power of *in vitro* testing may be valid using FEA (Anusavice *et al.*, 2007, Aboushelib *et al.*, 2007). FEA is a powerful tool which enables analysis of the location and intensity of stress in a specimen subjected to a load. FEA has been used successfully in dentistry in further understanding of the stress distribution and response of restorative materials to stress *in vivo* (Seymour *et al*., 1997, Asmussen *et al.*, 2005, Magne, 2007). Yet it is claimed that its use is not exploited enough (Magne, 2007). Using FEA in dental research has several advantages; it can be a more cost effective method of exploring research questions and conducting research. FEA can reduce the necessity to spend valuable resources on *in vitro* testing. It is also more time efficient, once an operator is trained, the modelling of different variables is relatively time efficient to carry out. FEA eliminates the variance in results, once a model is initially validated. This model is not subject to the anomalies or inhomogenieties which can occur with *in vitro* specimens. It is a useful tool when investigating complex systems that are difficult to standardize *in vitro* and *in vivo* (Eraslan *et al*., 2009). Employing FEA is a logical and progressive step in furthering the understanding of how endodontic access cavities impact on stress distribution within the structure of ceramic materials. FEA may be able to elucidate factors such as the effect of different shapes and sizes of access cavities, the effect of load angle, the location of maximum stresses, and even the response of layered ceramic systems.

The generation of a 3D Finite Element (FE) model requires an image, which can be obtained by modelling the shape and is the most time-consuming aspect of the process. Micro CT scanners have been used with success to obtain an image of a tooth (Magne, 2007). The image is then imported into a format which allows different areas to be separated i.e. enamel and dentine. The quality of the image is improved by remeshing the triangles whilst maintaining the geometry of the shape. The interfacial mesh between the enamel and dentine layers is re-established. Finally, the optimized information is imported into a FEA software package and the properties of the materials applied to the model (Magne, 2007). FEA has applications in the stress analysis of ceramics (Rekow *et al*., 2006, Sorrentino *et al.*, 2007, Wakabayashi *et al.*, 2008, Rafferty *et al.*, 2010, Sigal *et al.*, 2010). In relation to the endodontic access cavities in all-ceramic crowns, a FEA approach has been utilised in two studies (Cuddihy *et al*., 2013, Kelly *et al*., 2014).

There are limitations to the use of FEA, the materials are assumed to be homogeneous and isotropic. It does not account for porosity or cracks which may have been introduced to the materials during manufacture. Measurements are made under static conditions and not dynamic as is found intraorally. It is not possible to introduce thermal conditions (which can fluctuate quite considerably) which can affect materials in the oral environment. As previously discussed, failure of dental crowns *in vivo* is a complex area compounded by factors such as fatigue, moisture, temperature fluctuation, wear and damage. Materials are known to fail from fatique loading (Aboushelib and Elsafi, 2016). Unfortunately, it isn't possible to recreate these conditions using finite element (FE) models. While eliminating variability in specimens is a good approach for the realisation of strength properties, FEA cannot yield an indication as to the survival probability of a material in a given situation.

2.3.5 Summary of mechanical testing

Despite major advances in ceramic materials for all-ceramic restorations, which have resulted in their supplanting the provision of PFMs, ceramics may still be subject to brittle catastrophic failure *in vivo*. Clinical adjustments may cause damage and in the presence of moisture over time may contribute to failure. Extensive *in vitro* testing of ceramic materials is evident in the general dental literature, results provide useful information in relation to material ranking, however, inter-study comparisons are often not appropriate due to the different test variables and methods used to collect data. The use of FEA is becomingly more popular and can supplement information acquired through *in vitro* testing and even replace the need for labour intensive laboratory testing with models which have been appropriately validated.

Simulated *in vitro* laboratory tests fall short of replicating intra-oral biological events. In short, no single *in vitro* test can predict the performance of a material *in vivo*, but rather a combination of different *in vitro* tests should be used to evaluate a materials suitability for its intended intraoral purpose. Simple geometric shapes for testing materials permit a controlled, standardised approach to collecting data and making comparisons between materials. While a direct correlation between laboratory parameters and clinical events can be difficult to ascertain it does not undervalue laboratory tests, as they are useful in ranking different materials, as screening tools and for the evaluation of specific material properties. While the loading of anatomically shaped restorations may be more representative of the actual clinical situation, comparisons between data is more difficult (Abousheli *et al.,* 2007). Nevertheless, determination of the fracture toughness of a material, its flexural strength and resistance to failure in simulated intra oral conditions remain amongst the most popular and relevant properties for all-ceramic materials.

2.4 All-ceramic dental restorations

All-ceramic dental restorations are considered preferable to metal-ceramic restorations where high aesthetic outcomes are paramount to success. However, dental ceramics have conventionally lacked reliable strength characteristics, thus restricting their use to anterior restorations. PFM crowns have traditionally been the 'gold standard' for restorative dental care where the combination of high strength and good aesthetics are possible. Modern ceramic options now provide compelling alternatives to PFM's, high strength ceramics make them suitable alternative solutions for posterior restorations including bridgework. Ceramic materials are very biocompatible due to the fact that they are relatively inert in the oral environment. The ability to impart a high polish or glaze on the ceramic surface renders it resistant to plaque retention. Rising costs of precious metals and allergies to metals favour the all-ceramic trend and modern ceramic materials also suit the popular CAD/CAM market due to their machinability and dimensional stability. Ceramic materials can be formed into inlays, onlays, veneers, crowns, bridges, implants and can be either resin bonded or conventionally luted to tooth structure.

A myriad of dental ceramic materials are available, so many in fact that making a decision as to which one to use can be a challenge (Spear and Holloway, 2008). For the sake of simplicity, currently available ceramics can be broadly categorised as falling into two main categories namely glass-ceramics (feldspathic, leucite, lithium disilicate) or high-strength polycrystalline oxide ceramic, (zirconia) ceramics which are widely available and popular alternatives where PFM crowns may previously have been prescribed. Glass-ceramics generally lack sufficient mechanical properties to support their use in load-bearing areas. A selection of commercially available all-ceramic systems along with selected physical and mechanical properties are identified in Table 2.1.

Material	**Composition**	**Flexural strength**	**Fracture toughness**	**Hardness**
VM7	Feldspathic	60.1 ± 5.6 MPa (Kelly *et al*., 2014)	0.67 ± 0.05 MPa $m^{0.5}$ (Gonzaga *et al*., 2009)	
Vitablocs Mark II	Feldspar ceramic	110.9 ± MPa (Wendler et al., 2017)	1.37 ± 0.22 MPa $m^{0.5}$ (Charleton et al., 2008)	3.46 ± 0.15 GPa (Albero et al., 2015)
Empress	Leucite	133.5 ± 21.5 MPa (Cattell *et al*., 1997)	1.21 ± 0.05 (Gonzaga *et al*., 2009)	
Empress 2	Leucite	265.5 ± 25.7 MPa (Cattell *et al*., 2002)	1.57 ± 0.07 (Gonzaga *et al*., 2009)	
IPS Empress CAD	Leucite	137 ± 23.3 MPa (Charlton *et al*., 2008)	2.18 ± 0.3 MPa $m^{0.5}$ (Charleton et al., 2008)	4.60 ± 0.12 GPa (Albero et al., 2015)
IPS e.max® Press	Lithium disilicate	400 (Ivoclar Vivadent, 2011)	2.7 (Ivoclar Vivadent, 2011)	5.5 GPa (Albakry et al., 2003)
IPS e.max® CAD	Lithium disilicate	346.1 ± 67.3 (Gonzaga *et al*., 2009)	1.23 ± 0.26 (Gonzaga *et al*., 2009)	5.83 ± 0.07 GPa (Albero et al., 2015)
Vita Inceram® Alumina	Alumina	352 MPa (Wagner and Chu, 1996)	4.49 MPa $m^{0.5}$ (Wagner and Chu, 1996)	10.79 GPa (Rizkalla and Jones, 2004)
e.max ZirCAD	Zirconia	1303.21 ± MPa (Wendler *et al.,* 2017)	5.1 MPa $m^{0.5}$ (Ivoclar vivadent, 2017)	12 GPa (Ivoclar vivadent, 2017)
Prettau (Zirkonzahn)	Zirconia (translucent)	670 MPa (Zirkonzahn in house testing)		

Table 2.1. Mechanical properties of selected commercially available all-ceramic materials.

2.4.1 Feldspathic and silica glass-ceramics

Feldspathic and silica glass-ceramics materials are renowned for their aesthetic appeal due to a composition with a high level of glass phase, this renders them very translucent and capable of mimicking natural teeth to a high degree. The high glass content has the effect of compromising the mechanical properties, as a result this category of glass-ceramics are normally recommended for anterior restorations and contraindicated in the posterior region of the mouth. Clinical survival rates are reported to be significantly ($p<0.001$) lower for this category of ceramics compared with metal-ceramic or high-strength all-ceramic crowns (Sailer *et al*., 2015). The authors estimated a 5-year clinical survival of 90.7% (87.5-93.1%) for this group of materials and recommend restriction to the anterior region of the mouth.

Feldspathic and silica glass-ceramic materials are traditionally formed through a sintering process in the laboratory. Presintered blocks of feldspathic ceramic (Vitabloc Mark II) are commercially available for the CAD/CAM process, these have higher mechanical properties than sintered materials (Table 2.1). The use of this category of materials has somewhat diminished in recent years. This is most likely due to the equivalent aesthetic potential of ceramic materials with high mechanical properties such as LDGC or layered zirconia restorations. As discussed below these high strength ceramic materials offer greater versatility in relation to the fact that one material can be successfully used to provide a wide range of restoration solutions.

2.4.2 Lithium disilicate glass-ceramics (LDGC)

High strength LDGC's have been developed over the last decade for use initially using a heat-pressed manufacturing technique and have more recently been engineered to suit the CAD/CAM manufacturing process. IPS Empress 2 was the first generation heat-pressed LDGC restorative material from Ivoclar Vivadent which has now been replaced by IPS e.max® Press. The main differences are that IPS e.max® Press is more translucent, has a higher flexural strength and greater crystallinity. The material is comprised of 70% needle-like lithium disilicate ($Li_2Si_2O_5$) crystals embedded in a glass matrix containing SiO_2, K_2O, MgO, Al_2O_3, P_2O_5. The reinforced lithium disilicate crystals have an acicular morphology, with a high aspect ratio, measure 3–6 μm in length and 0.5–0.8 μm in width (Denry and Holloway, 2010) and form an interlocking microstructure (Figure 2.8). Tangential compressive forces are present due to the different thermal expansion coefficients and elastic moduli between the lithium disilicate crystals and the glass matrix. These forces promote the deflection of crack propagation under loading conditions (Apel *et al*., 2008, Denry and Holloway, 2010). This carefully engineered microstructure has given rise to the uniquely high flexural strengths which LDGC can withstand (typically in the region of 400 MPa) which is approximately a three-fold multiple of the more traditional (leucite and feldspathic) glass-ceramics. Similarly, it exhibits a comparatively higher fracture toughness compared with feldspathic and leucite glass-ceramics (Table 2.1). Gonzaga *et al.* (2009) concluded that materials with a higher fracture toughness such as lithium disilicate (IPS Empress 2) were less susceptible to SCG compared with porcelain (Vita VM7) or leucite (IPS Empress) glass-ceramics. SCG is a lifetime-limiting phenomenon, which affects all categories of ceramic materials in the presence of moisture (Gonzaga *et al.* 2011).

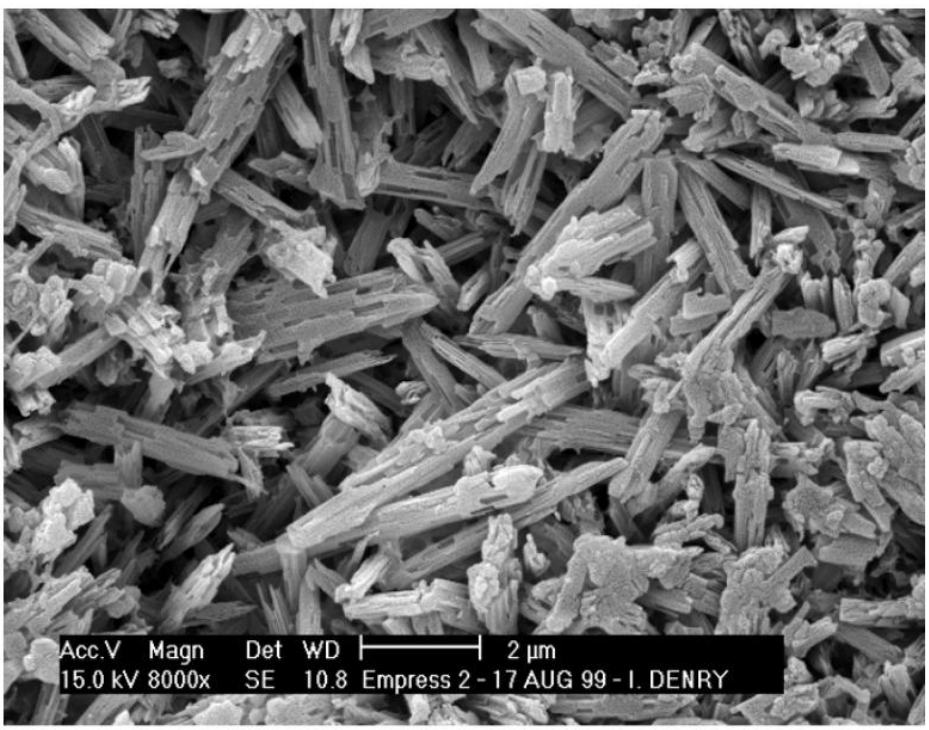

Figure 2.8 SEM image of lithium disilicate glass-ceramic, the lithium disilicate phase exhibits a rod-like morphology, which forms an interlocking microstructure (Denry and Holloway, 2010).

The current popularity of LDGC can be attributed not only to the exceptional strength characteristics for a material in the glass-ceramic category but also its ability to closely match the natural dentition due to its renowned optical properties (Zarone *et al*., 2016). It is available in several levels of opacity and translucency, i.e. high opacity (HO), medium opacity (MO), low translucency (LT), medium translucency (MT) and high translucency (HT). The wide choice of translucency options make it suitable for an extensive range of restorations such as inlays, onlays, veneers, full crowns and short span bridges (Ivoclar Vivadent, 2014). Polychromatic LDGC restorations are now possible using monolithic ingots that demonstrate a lifelike shade progression from the incisal to cervical area (IPS e.max® Multi-Press, Ivoclar). This negates the need to sinter a layer of translucent glass-ceramic on the core material and therefore any weakness associated with layering is eliminated. The ingots possess a graduated level of shade and translucency on par with that of natural teeth. A higher chroma (saturation) and opacity of the material can be located in the cervical and dentine areas, with increased translucency in the incisal region.

Compared with other ceramic core-veneer bilayered restorations (e.g. zirconia), delamination of the sintered layer from the core has not been a problem with lithium disilicate, but failure tends to involve both core and veneer fracture (Sundh and Sjogren, 2004). However, the failure rate of layered single crowns (1.83%) was found to be twice that of monolithic crowns (0.91%) in a 4-year retrospective study of over 21,000 LDGC restorations based on data retrieved from two commercial laboratories (Sulaiman *et al*., 2015).

A CAD/CAM method of producing restorations from LDGC is also available. IPS e.max® Press CAD (Ivoclar) presents a solid block of lithium metasilicate from which a restoration can be milled using computer generated data. The restoration requires subsequent heat treatment in a furnace to convert it from the metasilicate to disilicate form. CAD/CAM blocks of LDGC contain a high percentage of lithium metasilicate, which, due to the smaller crystal size permits greater machinability of the material with reduced wear of abrasive tools. The reported mechanical properties of the CAM processed material are lower (Table 2.1) than the heat-pressed material (Bompolaki *et al.,* 2015, Alkadi and Ruse, 2016). The reason for this can be explained by the difference in microstructure between the two materials, a larger crystal size (3–6 µm in length) which is optimal for LDGC is obtained using a heat-pressed method compared with the smaller crystal size (1.5 µm) of the CAD/CAM material. Alkadi and Ruse (2016) reported that fractured surfaces contained a higher degree of glass phase compared with the pressed material which exhibited a greater degree of crystallisation. It is suggested that the crystallisation cycle for IPS e.max® CAD does not allow the microstructure to develop to its maximum potential.

Cardelli *et al.* (2016) reported that the fabrication routes (pressed and CAD/CAM) had no significant (p = 0.154) influence on the *in vitro* failure load of lithium disilicate crowns. However, a higher Weibull modulus was reported for monolithic pressed crowns (m = 12.9) compared with monolithic CAD/CAM crowns (m = 8.8). Similarly, veneered restorations exhibited a higher 'm' value for pressed (8.8) compared with CAD/CAM crowns (5.8). Also, Lin *et al.* (2012) found no significant (p = 0.28) difference between both fabrication routes for flexural strength values of LDGC. These authors reported higher Weibull moduli (measure of statistical reliability) of the pressed material, for monolithic (1.5 mm thick) and veneered (0.8 mm core + 0.7 mm porcelain veneer) specimens, but found no difference for thinner (0.8 mm thick) monolithic specimens.

Reported clinical survival rates for LDGC single crowns in retrospective studies up to 11 years are between 86.1% - 98.2%, for both IPS Empress 2 and IPS e.max® Press systems (Valenti and Valenti, 2009, Valenti and Valenti 2015, Simeone and Gracis, 2015, Yang *et al*., 2016, Teichmann *et al*., 2017). Yang *et al*. 2016 recently reported a 96.7% survival rate based on a large 5-year retrospective study of 4,180 single e.max® Press crowns. Rauch *et al.* (2017) reported a survival rate of 87.6% for e.max® CAD crowns (n=41) after 6 years. Chipping and fracture were the most common reported reasons for failure in these studies, loss of retention and endodontic complications were also reported.

2.4.3 Zirconia oxide ceramics

Zirconia (ZrO_2) is a unique material which in many respects is a favourable dental restorative material due to its biocompatibility, white colour and high mechanical strength. It has been dubbed as ‘ceramic steel’ (Manicone *et al.,* 2007). It is chemically and structurally stable, and possesses the unique ability to ‘toughen’ under stress. This is achieved by initially stabilising the ZrO_2 with Y_2O_3, to be known as tetragonal zirconia polycrystal (TZP). When a stress is applied to the zirconia surface, the material undergoes a volumetric change from its tetragonal form to a monoclinic structure. The consequence of which is to expand the material and effectively ‘seal’ a potentially detrimental crack (Manicone *et al.,* 2007).

The use for zirconia in dentistry has grown over years and nowadays has a wide application including implant abutments, single crowns (monolithic or layered) and bridges. Large span implant bridges are possible but controversy exists around their reliability (Larsson *et al.,* 2006). A retrospective study of zirconia-based all-ceramic single crowns (n=137) reported a 98.5% survival rate at 5-years which decreased markedly to 67.2% at 10-years (Miura *et al*., 2017). The authors reported a significantly ($p<0.01$) higher failure rate for molar compared with anterior crowns. Rinke *et al*. (2015) reported a similar significant ($p=0.0058$) difference in survival depending on crown location. Chipping of the veneering layer was the most frequently reported complication in this study and is widely accepted as being a limiting factor to higher success rates (Guazzato *et al*., 2004, De Jager *et al.,* 2005, Aboushelib *et al.*, 2007, Sailer *et al*., 2015, Rinke *et al*., 2015).

Zirconia has been developed to suit the CAD/CAM market, which has become an immensely popular method for producing dental restorations. Restorations are designed using computer software, then milled from a partially sintered block of zirconia. The individual units when recovered are fully sintered at high temperatures (circa 1400ºC), then, either treated with surface stains to achieve the desired tooth shade or veneered with a sintered glass-ceramic layer. Aesthetically, the stain technique may be adequate for posterior restorations where appearance is less critical. The relative opacity of zirconia is one of the major limitations of its use, especially in the anterior region of the mouth. Zirconia cores can be laminated with a sintered glass-ceramic veneer to achieve a natural appearance. This weaker veneering porcelain of the bilayered system may offset the positive strengthening effect of the core materials on the overall strength (Guazzato *et al*., 2004, Aboushelib *et al.*, 2007).

Chipping and delamination of the sintered layer is problematic and a common mode of failure in bilayered systems (Aboushelib *et al.,* 2006). The reasons for which are multi factorial and include stresses caused by differences in the CTE of the core and veneering ceramic, inadequate adaptation of the veneer ceramic to the core substructure, thermal or stress induced zirconia transformation at the core-veneer interface and fabrication induced flaws (De Jager *et al.,* 2005). Investigation into the mechanical properties of bilayered ceramics is a complex and inadequately understood area of research. In addition, quite a range of materials is found to be classified as zirconia, ranging from low strength (700 MPa) high translucency, to high strength (1200 MPa) low translucency, zirconia (Zhang, 2014).

The pore size and population, the presence of defects, impurities and grain boundaries in the ceramic body can greatly influence the translucency of zirconia. In addition, TZP has been described as birefringent, which means that the refractive index is anisotropic in different crystallographic directions, which further acts to reduce light transmission (Zhang, 2014). Zirconia ceramics with higher translucency have been developed to overcome difficulties with opacity and its restriction to posterior restorations in its monolithic form. This microstructural tailoring can be been achieved with increased density of the ceramic body (i.e. elimination of pores) and incorporation of a transparent form of cubic yttrium stabilised zirconia (Zhang, 2014). However, this is not easily achieved and is associated with a very significant (up to 50%) decrease in mechanical properties (Zhang, 2014).

In an era where resin bonding is a popular choice for the cementation of restorations, adhesion to zirconia has presented a challenge (Tzanakakis *et al.,* 2016). Adhesion to zirconia is a controversial topic, some authors advocate that it's possible (Manicone *et al., 2007*) while others have shown that it is unsatisfactory (DeSouza *et al*., 2014). This is discussed in further detail in Section 2.4.4.

2.4.4 The role of resin composite luting cements

Tooth-supported permanent dental restorative systems function typically as a combination of tooth structure (dentine, enamel), luting material (resin composite, glass ionomer, zinc phosphate) and restorative material (metal, ceramic). Of the many luting agents available for the definitive cementation of restorations to teeth, resin composites are by far the most suitable and widely used with glass-ceramic restorations (Manso *et al.,* 2011). Research into the mechanical properties of resin composite material has been prolific in recent years. Resin composite forms a strong interface between tooth and restoration, as it bonds micromechanically to enamel and dentine and chemically to etched and silanated glass-ceramics (Diaz-Arnold *et al.,* 1999).

The adhesion of resin composite to zirconia is difficult to achieve, the absence of a glass phase renders zirconia resistant to acid etching and the formation of a chemical bond. Several surface treatments have been attempted to improve this, which include, alumina particle abrasion, selective infiltration etching and tribochemical coating, various degrees of success have been achieved (Tzanakakis *et al.,* 2016). Application of phosphate acid ester monomers (MDP (10-methacryloyloxydecyl dihydrogen phosphate)) have shown promising results however, while initially high bond strengths are sometimes achievable, these values decrease over time as a result of water hydrolysis (De Souza *et al.,* 2014). A 7-year observational study reported a high rate (31 of 323 restorations) of debonding for zirconia restorations (Rinke *et al*., 2015), loss of retention has also been reported as a complication in other retrospective studies for this material (Güncü *et al*., 2015, Näpänkangas *et al*., 2015).

Resin composite can be light and/or chemically activated, and bonding to enamel is achieved through micromechanical retention and is largely very successful. However, achieving a predictable bond to dentine can prove more problematic due to the relative moisture content and unfavourable structure of dentine. Dentine bonding is possible, but technique sensitive and involves multi-steps to ‘prime’ the surface by demineralising the dentine and widening the dentine tubules for ‘adhesion’ through micromechanical retention of the resin composite cement (Diaz-Arnold *et al.,* 1999). Control of the acidity of the luting cement is also important to avoid pulpal irritation; at the delivery of the definitive crown, the pulp is likely to be sensitive and every opportunity to protect it must be taken (Section 2.1.3). The strong bond which resin composite mediates between tooth and restoration make it suitable for cementing restorations to non-ideal tooth preparations and indeed less-than-ideal fitting restorations. Resin composite is virtually insoluble in oral fluids which helps overcome the solubility issues observed with other luting agents such as zinc phosphate and glass ionomer cements, these critically rely on close fitting restorations to prevent marginal solubility.

Resin composite has higher compressive and diametrial tensile strengths compared with other popular luting agents such as zinc phosphate, glass-ionomer and resin modified glass-ionomer. Resin composite cementation is associated with increasing the fracture strength of glass-ceramic restorations (Burke *et al*., 2002). The reason for this is complex, suggestions include the increase in MOE of the resin composite when it adheres to the glass-ceramic (Spazzin *et al*., 2017). Current clinical trends involve the use of fewer steps in the bonding protocol, this has led to the introduction of self-etch and self-adhesive resins, however these materials usually have a lower pH and higher absorption of water compared with their original counterparts.

The viscosity of the resin cement has been shown to influence microleakage (Hahn *et al*., 2001). *In vitro* tests show that higher viscosity resin composite cements result in a significantly lesser degree of die penetration. The influence of the interface location was significant, dye penetration at the ceramic-resin interface was lower than at the dentine-resin interface. Higher viscosity cements were shown to provide a better seal at the dentin-composite margins for a larger luting space (406 µm). For ideal luting spaces (27 µm) the viscosity of the luting cement had no influence on the seal. *In vitro* test loading was also found to increase the depth of dye penetration.

The importance of an adequate seal between the prepared tooth and restoration through cementation, cannot be overstated. The fit of a restoration can be controlled through operative techniques in both clinical and technical domains. However, despite observation of best practice throughout all procedures, marginal adaption can depreciate with time. One of the major causes of bond failure of resin composite continues to be shrinkage on polymerisation which can result in detrimental contractional voids especially in areas of substantial thickness (Davidson *et al*., 1984). Thermal fluctuations in the oral environment may lead to bond fatigue due to a mismatch in the coefficient of thermal expansion between the dentine and resin resulting in stresses from the expansion and contraction of both materials and degradation of the marginal ‘seal’. Bond failure may also occur due to strain from repetitive shearing forces in the mouth. Ultimately, the loss of marginal seal can lead to microbial ingress between the tooth and restoration, caries can become re-established and pulpal involvement may occur beneath the restoration. This will necessitate the need for endodontic intervention.

2.5 Endodontic access through dental crowns - Summary of the existing literature

In 1974, a vented crown (opening on the occlusal surface) was proposed to facilitate contingency planning for a tooth with a poor prognosis, this would permit endodontic treatment to be executed *in situ* with minimal trauma to the crown restoration (Burrell and Goldberg, 1974). For such extreme measures to be considered by the authors, the need for endodontic treatment has and continues to be a very significant clinical concern after crown placement. However, by today's standards provision of a vented crown would not be considered an acceptable treatment option.

The earliest article identified in the literature, which reports the procedure for gaining endodontic access through a crown, was in 1962 (Michanowicz and Michanowicz, 1962). The authors described the procedure for creating an endodontic access cavity through PJC's *in vivo*. Despite the relatively high incidence of endodontic therapy through pre-existing crowns (Goldman *et al.*, 1992, Trautmann *et al.,* 2000a), relatively few studies have been published over these past 55 years in this subject area (Gorman *et al.,* 2016). No known randomised control trial, retrospective or prospective clinical studies were identified in the literature. Such information would be useful to inform clinical survival probabilities (Teplitsky and Sutherland, 1985, Sutherland *et al*., 1989, Gorman *et al.,* 2016).

The use of all-ceramic crowns has increased dramatically over recent years and are strong contenders as alternative treatment options to PFM's (Sailer *et al*., 2015). All-ceramic crown perforation for endodontic treatment is more challenging compared with metal or metal-ceramic equivalents (Davis, 1998). All-ceramic crowns warrant special consideration for endodontic access, since ceramics are brittle and known to fail catastrophically. Few clear guidelines for the endodontic access of all-ceramic crowns in particular exist in the literature (Davis, 1998, Schwartz and Fransman, 2005, Gorman *et al.,* 2016).

2.5.1 All-ceramic dental crown materials

The all-ceramic crown materials used in the various studies identified in the literature encompass almost every development in dental ceramic materials over the past 55 years (1962-2017) and generally were selected from what was largely current and popularly available at the time. Endodontic access cavities or simulations were carried out through sintered alumina (PJC) (Michanowicz and Michanowicz, 1962, Stokes *et al.,* 1988), sintered feldspathic porcelain (VM7) (Kelly *et al.,* 2014, Kelly *et al.,* 2017), heat-pressed magnesia alumina (Cerestore) (Teplitsky and Sutherland, 1985), fluoromica (Dicor) (Sutherland *et al.,* 1989, Cohen and Wallace, 1991), heat-pressed leucite (IPS Empress) (Haselton *et al.,* 2000, Sabourin *et al.,* 2005), presintered CAD/CAM leucite (IPS Empress CAD) (Kelly *et al.,* 2017), heat-pressed lithium disilicate (IPS e.max® Press) (Qeblawi *et al.,* 2011, Bompolaki *et al.,* 2015), CAD/CAM lithium disilicate (IPS e.max® CAD) (Bompolaki *et al.,* 2015), CAD/CAM alumina core and sintered glass-ceramic veneer (Wood *et al.,* 2006) and CAD/CAM zirconia core and sintered glass-ceramic veneer (Wood *et al.,* 2006, Grobecker-Karl *et al*., 2016) crown materials.

2.5.2 Damage at the endodontic access cavity

While minor adjustments are routinely carried out to improve fit and occlusion, the process can induce damage which may make the restoration susceptible to premature failure (Section 2.3.2.2). Trephining an endodontic access cavity *in situ* is a very significant 'adjustment' to an existing all-ceramic crown and many *in vitro* studies have reported the damage caused at the access cavities (Teplitsky and Sutherland 1985, Stokes *et al.,* 1988, Sutherland *et al.,* 1989, Cohen and Wallace 1991, Haselton *et al.,* 2000, Sabourin *et al.,* 2005, Wood *et al.,* 2006, Qeblawi *et al.,* 2011, Bompolaki *et al.,* 2015, Grobecker-Karl *et al*., 2016).

Sabourin *et al.* (2005) investigated the damage caused by preparation of endodontic access cavities (3 mm diameter) in ceramic discs using, air abrasion (27μm aluminium oxide grit), diamond and tungsten carbide instrumentation. Catastrophic fractures (3 out of 16) occurred in the diamond bur group. The air abrasion method was found to be significantly ($p<0.0001$) different from diamond and tungsten carbide burs, in that no detectable damage (edge chipping or microcracks) to the specimen was found. However, the mean preparation time required (69.3 seconds) was significantly longer than for diamond (25.3 seconds) or tungsten carbide (34.0 seconds) burs. Carbide burs caused significantly more microcracks than diamond burs ($p=0.0003$) or air abrasion ($p<0.0001$) when using fluorescent liquid ultraviolet dye penetrant (UVDP) detection. UVDP was significantly more sensitive at detecting microcracks than white light (WL) transillumination. The authors concluded that UVDP was a more sensitive detection method for microcracks, and suggested that “prior papers may have under-reported the damage caused by burs”. Fluorescent die penetration (FDP) has been shown to be a more sensitive method for crack detection compared with transillumination (Beck *et al*., 2010). The authors found that 37% of cracks detected with FDP in feldspathic and 64% in zirconia ceramic plates could not be detected with transillumination. Some method of visual quality control of the crown was thus recommended prior to the decision to proceed with the endodontic access cavity repair.

Descriptive details of the damage around the access cavity included chipping in 69% (Sutherland *et al.*, 1989) and in 100% (Teplitsky and Sutherland, 1985, Haselton *et al.*, 2000, Wood *et al.*, 2006 and Bompolaki *et al.* 2015) of specimens examined. Microcracks around the access cavity were reported in 14% (Haselton *et al.,* 2000) and 1.8% (Teplitsky and Sutherland, 1985) of ceramic specimens. Radial cracks (Figure 2.9) present in three crowns after endodontic access preparation were associated with the lowest recorded failure loads (Wood *et al.,* 2006). Catastrophic crown fracture was an event which was noted during access cavity preparation in three studies (Sutherland *et al.,* 1989, Cohen and Wallace, 1991, Haselton *et al.,* 2000), a high incidence of mandibular incisor fractures (Sutherland *et al.,* 1989) occurred during access cavity preparation, probably as a result of increased cavity to crown size ratio.

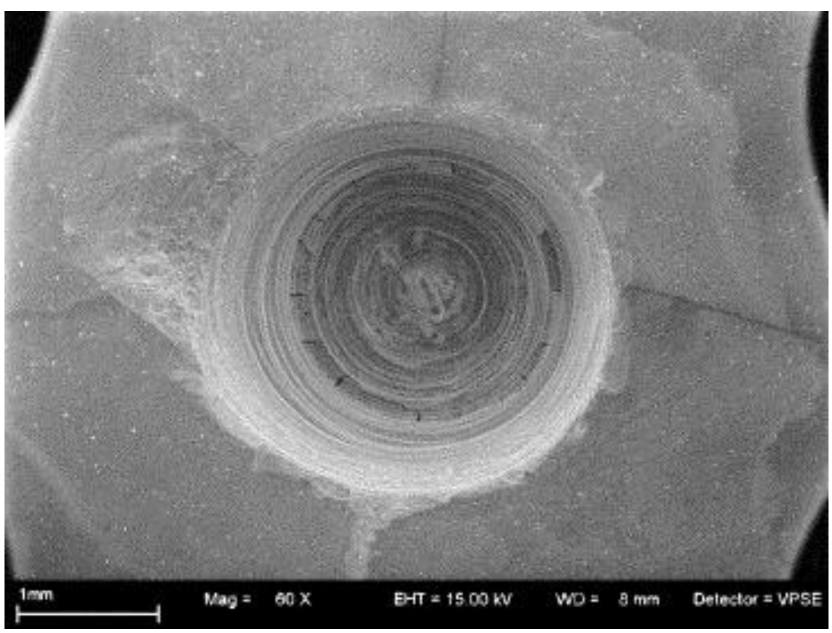

Figure 2.9 Environmental SEM image (X60) of zirconia crown with an endodontic access cavity, note the radial cracks evident eminating from the cavity (Wood *et al.*, 2006).

Haselton *et al.* (2000) fabricated twenty-eight IPS Empress crowns (IPS Empress, Ivoclar, North America, Amherst, NY, USA) for extracted premolar teeth which were divided into two groups (n=14). Access cavities were prepared using either a diamond or tungsten carbide bur for each group. SEM was carried out before and after access preparations, microcracks and edge chipping were found universally in all specimens, three specimens exhibited total fracture. No statistical difference (p=0.072) was found between bur types for rates of damage recorded in edge chipping, microcracks and fracture. The authors suggested that the use of profilometry could yield a greater appreciation of the damage observed. The authors commented on the difficulty experienced in comparing this study to that of others due to a lack of standardised reporting terminology. As a result, they proposed a classification for the defects frequently observed with access cavity instrumentation in all-ceramic crowns, Wood *et al.* (2006) subsequently made use of these criteria.

Another study found tungsten carbide burs to be totally ineffective in cutting Cerestore crowns (n=4) compared with diamond burs (n=52) (Teplitsky and Sutherland, 1985). Twelve randomly selected crowns were further inspected using direct vision, stereomicroscope and transillumination. The authors detected a crack for only one crown, chips around the access cavity were generally evident. Sutherland *et al.* (1989) reported that carbide burs caused more fractures of Dicor crowns than diamond burs during endodontic access cavity preparation. The crowns were inspected visually, using transillumination, stereomicroscopy and SEM. Seven crowns were described as exhibiting craze lines, 29 with chipping adjacent to the access cavity whilst 2 fractured during the access procedure.

2.5.3 Repair of the endodontic access cavity in all-ceramic crowns

Endodontic access cavities in all-ceramic crowns are usually repaired with a resin composite (Trautmann *et al.,* 2000b, Schwartz and Fransman, 2005). Most operators choose to carry out a repair, most importantly to protect against coronal leakage (Trautmann *et al.,* 2000b), a repair also restores tooth shape and occlusal contact. It is not unreasonable to assume that the strength of the crown is compromised when an access cavity is prepared, however it is not clear whether the strength (or service life) of the crown can in some way be improved or restored when a repair is placed. Stokes *et al*. (1988) reported no significant difference in failure load of maxillary incisor PJCs when the access cavity repair protocol was varied (inclusion of silane primer). Clinical repair protocols addressing endodontic access cavities specifically in all-ceramic crowns are lacking in the literature. Rather these seem to be based on manufacturer's instructions for intraoral ceramic repair and the empirical decision of the operator. Certain materials used in the root canal treatment procedure such as sodium hypochlorite (canal irrigant) and eugenol-based materials can interfere with the resin composite-ceramic repair (Davis, 1998, Schwartz and Fransman, 2005). The ceramic access cavity margins should be thoroughly cleaned with a solvent and or acid prior to application of resin composite to eliminate this potential interference.

2.5.4 Luting agents for the cementation of restorations

The luting agents used in the *in vitro* studies identified in the literature would appear to have been selected due to popularity and what was recommended at the time each study was conducted. Specifically, luting agents were also chosen for retrievability (Teplitsky and Sutherland, 1985, Sutherland *et al.,* 1989), to investigate variation in repair protocol (Stokes *et al*., 1988) and to compare the effect of the luting agent on the fracture resistance (Qeblawi *et al.,* 2011) or microcrack formation (Cohen and Wallace, 1991).

2.5.5 Mechanical properties of endodontically accessed all-ceramic crowns

Variables that influence the failure load of endodontically accessed all-ceramic crown restorations have been identified (Gorman *et al.,* 2016) from four studies (Stokes *et al.,* 1988, Wood *et al.,* 2006, Qeblawi *et al.,* 2011, Bompolaki *et al.,* 2015). The access cavity dimensions prepared in these studies varied from 3 mm triangular (Stokes *et al.,* 1988), 3.5 mm round (Wood *et al.,* 2006, Bompolaki *et al.,* 2015) and unspecified (Qeblawi *et al.,* 2011). The dimension of the access cavity was not examined as a factor in relation to failure load in any of the studies. A smaller crown size inevitably has an increased ratio of cavity to crown size and may be responsible for the observed increased incidence of failure during endodontic procedures (Sutherland *et al.,* 1989). A limitation in all four studies was the lack of a control groups (unrepaired crown) in the study designs.

The effect of the repair bonding protocol for endodontic access cavities on the failure load of sintered alumina crowns (n=10) was investigated by Stokes *et al.* (1988). The original failure load (487 ± 10 N) was significantly reduced (359 ± 118 N, $p < 0.05$) with the introduction of an access cavity repaired with composite, this value was statistically uninfluenced (354 ± 58 N, $p < 0.001$) by variation (inclusion of silane primer) in the repair protocol.

Wood *et al.* (2006) found no significant ($p<0.695$) difference in failure loads between intact (1410 ± 111 N) versus repaired (1436 ± 223 N) alumina crowns (n=12), but reported a significant ($p<0.006$) difference between intact (2432 ± 181 N) versus repaired (2075 ± 348 N) zirconia crowns (n=12). However, for both materials the standard deviation approximately doubled for the repaired groups and the Weibull modulus approximately halved (12.8-6.2 and 13.4-5.4, respectively).

Qeblawi *et al.* (2011) prepared access cavities in lithium disilicate crowns (n=10) and found that a 180 µm grit sized diamond bur significantly ($p < 0.05$) lowered the mean load to failure (2354 ± 476 N) compared with the intact crowns (3316 ± 483 N) and a 126 µm grit sized diamond bur (3464 ± 645 N), however this was not found to be significantly ($p=0.14$) different from the 150 µm grit sized diamond bur (2915 ± 569 N). The larger flaw size introduced into the surface of the ceramic with the larger grit sized diamond bur would reasonably explain this, however no imaging was carried out to substantiate this effect. The Qeblawi *et al.* (2011) study also compared the effect of luting cements on the failure load. Zinc phosphate cementation was associated with lower failure loads compared with resin luting agents. The lowest failure loads were recorded when cemented with zinc phosphate for the intact crown (2242 ± 369 N) and the 126 µm bur group (1999 ± 448 N), these were statistically ($p<0.001$) different from the corresponding resin bonded groups and the 150 µm grit bur group ($p<0.05$). Higher failure loads (excess of 3000 N) were reported in this study, crowns that were luted with resin composite produced the highest failure loads, and this could be explained by adhesion to the resin composite die substrate material. Interestingly, a high percentage (100%) of crown (lithium disilicate) and substrate (resin composite) failures were reported for 50% of all specimens. Failure loads recorded above 2915 N all exhibited a crown and die failure mode, whereas for lower failure loads (2354 N, 2242 N, 1999 N) the percentage of combined failures decreased proportionally (60%, 50%, 30%, respectively). The authors attributed this to the relatively low MOE (10 GPa) of the resin composite die substrate materials used. The MOE of the crown support material has been shown to significantly influence the failure load of all-ceramic crowns (Scherrer and deRijk, 1993). The MOE of the substrate on which a restoration is placed influences its structural performance (Scherrer and deRijk, 1993, Wang and Darvell, 2012). Substrates with higher elastic moduli such as metal are associated with higher load bearing capacities (Lee and Wilson, 2000) compared with lower moduli substrates such as dentine or glass-ceramics (Malament and Socransky, 2001).

Bompolaki *et al.* (2015) recorded a significantly ($p \leq 0.001$) higher failure load for pressed (1901 ± 349 N) versus milled (1573 ± 267 N) lithium disilicate intact crowns. Preparation and repair of an access cavity reduced the failure load from 1429 ± 384 N to 1297 ± 329 N for pressed and milled crowns, respectively. In this study the crowns were stored for three weeks in saline and subjected to cyclic loading fatigue in a dry state prior to testing. The large differences observed for failure load observed between the Qeblawi *et al.* (2011) and Bompolaki *et al.* (2015) studies could be attributed to variances in the experimental methodology applied for ageing and storing specimens prior to testing in addition to the aforementioned explanation in relation to bonding to the resin composite die material. Bompolaki *et al.* (2015) highlighted that failure loads of accessed and repaired crowns were higher than average forces generated in the oral environment (720 N) and could potentially provide a serviceable restoration with a long-term prognosis. However, the Weibull modulus for the intact pressed (5.9) and milled (6.5) crowns reduced when endodontically accessed and repaired, to 3.9 and 4.5, respectively.

Two recent studies investigated the effect of screw access channels on the failure load of implant, supported ceramic dental crowns (Hussien *et al.,* 2016, Mokhtarpour *et al.,* 2016). A potential analogy between screw access and endodontic access cavities exist. No difference in failure load between intact crowns versus crowns with screw access channels fabricated from zirconia, veneered zirconia and lithium disilicate was reported (Hussein *et al.* 2016). Significant ($p>0.05$) differences in failure load were recorded for the different ceramic materials used. The veneered zirconia restoration with a screw access channel had the lowest recorded failure load (411 ± 34.4 N) compared with the equivalent monolithic zirconia restoration (2047.8 ± 83.2 N). However, the study did not define what determined failure, therefore arguably the veneered restoration may not have failed via fracture of the zirconia core but rather as a result of delamination of the veneering porcelain, in which case the comparison could be deemed inappropriate. The study also failed to report the fracture origin, mode or any such descriptive data which may have yielded further information.

Similarly, no information regarding fracture data was provided in the Mokhtarpour *et al*. (2016) study, which investigated the effect of machining (prior to sintering) or manually grinding (after sintering), a screw access cavity in zirconia crowns. Specimens which exhibited fracture of the veneering ceramic without fracture of the core material were eliminated from the data, the group size was initially relatively small (n=10) and the final numbers of specimens included in the analysis were not provided, thus the 'robustness' of the data may be questioned. The failure loads reported, for intact crowns (888.37 ± 228.92 N), crowns with access channels machined prior to sintering (610.48 ± 125.02 N) and crowns with access channels manually prepared after sintering (496.74 ± 104.10 N) were low compared with other studies. Statistically significant ($p<0.0001$) differences were found between the intact versus both screw access channel groups, but no significant ($p=0.44$) difference was found between the screw access channel groups. Again, additional descriptive data were not reported.

Flexural strength may be determined though fractographical examination of fractured crown specimens (Quinn *et al*., 2005), however this is very difficult to perform. Two studies have been identified which determine the impact of endodontic access cavities on the EBFS of feldspathic and leucite glass-ceramic dental crown materials. Novel analytical solutions were proposed to account for the annular effect of the access cavity on the biaxial flexural strength of the material (Kelly *et al*., 2014). Further work by the same group of researchers determined that the application of a thin layer of resin composite luting material prior to machining a representative endodontic access cavity in ceramic plates maintained the EBFS for feldspathic materials but not for leucite glass-ceramics (Kelly *et al.*, 2017). The authors recommended that for leucite glass-ceramics, replacement and not repair of the restoration should be the preferred option clinically.

2.5.6 The effect of endodontic access on the retention of dental crowns

While it was not the intention of this thesis to investigate the issues around retention or microleakage of endodontically accessed and repaired restorations, the following short discussion is included to complete the literature review and consider the implications these aspects may have on all-ceramic restorations. These issues are given further consideration in the suggestions for further research (Section 7.2).

The effect of crown retention as a result of endodontically accessing dental crowns is discussed below. A decrease in retention was reported for anterior maxillary incisor PFM's after an endodontic access cavity was prepared (McMullen *et al.,* 1989). In a subsequent study the authors reported that the retention lost as a result of preparing an access cavity, could be restored when the cavity was repaired with amalgam (McMullen, 1990). The retention value succeeded that of the original value, for crowns cemented with zinc phosphate (n=9) by 126% and those cemented with polycarboxylate (n=9) by 237%. The depth of the repair material into the tooth and tangential direction (lingual cavity in maxillary incisors) in relation to the path of withdrawal and was suggested as a reason for the significant improvement in retention.

Yu and Abbott (1994) reported no significant ($p<0.05$) difference between the initial mean retentive force (24.5 ± 14.5 kg) required to remove intact crowns and the mean force (19.9 ± 8.8 kg) required to remove crowns which had endodontic access cavities prepared. The access cavity was subsequently restored with amalgam and the retention was regained but this was not significantly ($p<0.05$) different. A significant difference ($p<0.05$) was however observed when access cavities were restored with a post. Another investigation showed that cutting an access cavity in a crown had the effect of significantly ($p<0.05$) reducing crown retention, subsequent repair with amalgam or glass ionomer cement increased the retention in excess of original values (Mulvay and Abbott, 1996). The authors observed a correlation between increased area of the access cavity and reduced crown retention.

While no equivalent study which investigates the effect of endodontic access cavity preparation on the retention of all-ceramic crowns exists, it is apparent the difficulties which would be encountered in performing similar tests for all-ceramic crowns, given the brittle nature of ceramics. Cohen and

Wallace (1991) incidentally noted loss of retention for 100% (n=3) of fluoromica crowns cemented with zinc phosphate cement compared with polycarboxylate cement after root canal treatment was performed. The adhesive interface formed between glass-ceramics and tooth structure could prevent crown dislodgement during access cavity preparation so long as the adhesive interface was maintained. However, for non-adhesively cemented crowns such as zirconia, loss of retention may become an issue when endodontic treatment has been performed through the crown in a similar manner to that of metal or metal supported crowns. As discussed in Section 2.4.4, there is some potential to adhesively bond zirconia, however it is contentious and somewhat unreliable.

2.5.7 Microleakage of endodontically accessed dental crowns

Microleakage is defined as the clinically undetectable “passage of bacteria, fluids, molecules, or ions between a cavity wall and the restorative material applied to it” (Kidd, 1976). Prevention of coronal leakage at the access cavity may be crucial to maintaining the crown as a permanent restoration (Trautmann *et al.,* 2000b). To this end, no evidence-based research is available to recommend restorative materials for the repair of the endodontic access cavity in all-ceramic crowns, but rather, selection is based on empiricism and personal preference (Trautmann *et al.* 2000b). Four studies were identified which investigated microleakage in crowned teeth which had been endodontically accessed and restored (Trautmann *et* *al.,* 2001a, Trautmann *et al.,* 2001b, Al-Maqtari and Lui, 2010, Al-Moaleem *et al.,* 2011). Trautmann *et al.* (2001a and 2001b) conducted a two-part microleakage study which compared various restorative materials for repairing the access cavity in different crown types. The first part of the study recorded turbidity, as a measure of microbial penetration which resulted from bacterial leakage in different crown types (all-ceramic, PFM, full metal) restored with various restorative materials (amalgam, resin composite, glass-ionomer) (Trautmann *et al.,* 2001a). All restorative materials demonstrated significant leakage however, no significant association ($p=0.149$) between leakage and crown type with choice of repair material was made. All-ceramic crowns (IPS Empress, Ivoclar) showed the highest amount of leakage ($p=0.046$) compared with non-all-ceramic crown types. Posterior all-ceramic crowns exhibited a significantly higher incidence ($p=0.045$) of leakage compared with posterior PFM crowns. Part two of the same study involved the same specimens which were recovered from the turbidity tests and stored in a die tracer (2% methylene blue) for 30 days after which the depth of die penetration was measured (Trautmann *et al*., 2001b). While all materials showed significant die penetration, dual-cured resin composite and glass-ionomer cement exhibited the greatest depth of dye penetration at both the access cavity margin and the tooth crown margin. All-ceramic crowns had significantly ($p<0.0001$) greater die penetration than full metal crowns.

The inclusion of a flowable nanocomposite (Filtek Z350, 3M Espe) in the repair protocol of endodontic access cavities in model PFM discs demonstrated a slight reduction in coronal microleakage but was not found to be significant (p=0.135) (Al-Maqtari and Lui, 2010). The rationale with using a flowable resin composite was that it would form an elastic layer which would reduce polymerisation shrinkage. This study determined that specimens stored for 7-days had significantly less (p=0.002) coronal microleakage compared with those stored for 1-day. Coronal microleakage was found to significantly (p=0.000) decrease with thermocycling compared to without thermocycling (p=0.735). This was attributed to accelerated diffusion between both resin composite and ceramic/metal substrates facilitated by the generation of stress from differing material CTE's.

The ability of three restorative materials (amalgam, resin composite and compomer) to prevent microleakage of repaired access openings was measured in PFM discs with representative endodontic access cavities (Al-Moaleem *et al.,* 2011). Amalgam exhibited the highest level of leakage followed by resin composite and compomer had the least. The levels of microleakage in resin composite increased with greater number of thermocycles, this was attributed to bond degradation. Compomer had the lowest levels of microleakage, this was attributed to less shrinkage initially, followed by subsequent water absorption. Prolonged thermocycling increased the depth of dye penetration for all groups.

2.6 Chapter summary

- The prevalence of endodontic treatment with a dental crown *in situ* is high. The link between endodontic pathology and crown provision is evident. All-ceramic crowns are increasingly being used to restore teeth in all positions of the oral cavity. Endodontic access cavities are challenging to prepare in all-ceramic crowns due to the high strength of modern materials, these are usually repaired with a resin composite material. Existing *in vitro* studies in this subject area to support clinical protocols are conspicuously few in number.

- The impact of the dimension and geometry of the access cavity on the failure load of the crown is unclear. While much is known about the response of ceramics to damage, the impact of access cavities in complex geometries such as dental crowns combined with complex loading conditions has yet to be ascertained.

- The influence of the access cavity repair material and the modulus of elasticity of resin composite as a repair material on failure load is also unknown.

- Endodontic access cavities in dental crowns may cause a potential loss of retention especially for non-adhesively luted crowns i.e. with a metal or zirconia intaglio surface. The extent of the access cavity on retention is also potentially influential.

- The potential for FEA as an exploratory tool for examining variables in relation to the above is relatively underused to date.

Chapter 3

The effect of endodontic access on all-ceramic crowns: A systematic review of *in vitro* studies

This chapter has been published as

The effect of endodontic access on all-ceramic crowns: A systematic review of *in vitro* studies.

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Abstract

Objectives: The aim of this systematic review was to identify from *in vitro* studies the effect of endodontic access on the fracture resistance of all-ceramic crowns and to investigate the evidence of damage around the access cavity.

Data: The articles identified were screened by two reviewers according to inclusion and exclusion criteria. The reference lists of articles advanced to second round screening were hand searched to identify additional potential articles. The risk of bias for the articles was independently performed by two reviewers.

Sources*:* An electronic search was conducted on PubMed/Medline, Web of Science, Scopus and Embase databases with no limitations.

Study selection: 383 articles were identified, of which, eight met the inclusion criteria and formed the basis of this systematic review. Factors investigated in the selected articles included the, presence of microcracks at the access cavity, repair protocol, ceramic type, crown fabrication method, luting agent and grit size of the diamond bur. The risk of bias was deemed to be high for three, medium for two and low for three of the reviewed studies. The high level of heterogeneity across the studies precluded meta-analyses.

Conclusion: Based on the currently available scientific evidence, a 'best practice' protocol with regard to improving the fracture resistance of endodontically accessed and repaired all-ceramic crowns cannot be

conclusively identified. However, some key factors which potentially impact on the fracture resistance of endodontically accessed and repaired all-ceramic crowns have been isolated. Cautious clinical interpretation of these factors is concluded for the maintenance of the crown as a permanent restoration.

Clinical significance

Key factors which impact on the fracture resistance of endodontically accessed and repaired all-ceramic crowns have been isolated from *in vitro* studies. Cautious clinical interpretation of these factors is advised for the maintenance of the crown as a permanent restoration.

3.1 Introduction

The provision of dental crowns represents a sizeable proportion of treatment units provided to patients presenting to the General Dental Services (GDS) in England and Wales with over 1.1 million dental crowns placed annually (Burke and Lucarotti, 2009b). Additionally, dental crowns are frequently the treatment modality of choice for US dentists with approximately one crown being provided to every 2.3 US adult patients in 2012 (Christensen, 2013). The increased incidences of patient treatment with dental crowns in general dental practice (Kelleher, 2012) is often in preference to less destructive options including bleaching, resin composite (RC) restorations or minor orthodontic treatment (Kelleher, 2012, Christensen, 2013). Dental crowns are perceived to be a durable and uncomplicated option whilst simultaneously generating the highest income (Christensen, 2013). However, crown preparation is irreversibly destructive to tooth tissue, typically 62-73% of tooth structure is removed during preparation for anterior all-ceramic crowns (Edelhoff and Sorenson, 2002). The link between tooth destruction and possible pulpal complications is well documented in the dental literature (Dahl, 1977, Bergenholtz, 1991, Jackson *et al*., 1992, Goodacre and Spolnik, 1994, Christensen, 1997, Edelhoff and Sorenson, 2002, Christensen, 2005).

Goodacre *et al*. (2003) reviewed the literature to investigate the incidence of clinical complications of dental crowns over a 50-year period. The authors combined the results of five studies (Lundqvist and Nilson, 1982, Cheung, 1991, Jackson *et al*., 1992, Milleding *et al*., 1998, Walton, 1999) and identified that 3% (27 of 823) of dental crowns required subsequent endodontic treatment. A 2.1% incidence of loss of vitality after all-ceramic crown placement was calculated from a meta-analysis of 34 studies within a 5-year period (Pjetursson *et al*., 2007). A retrospective analysis of 47,474 crowned teeth in the GDS over a ten-year period (1991-2001) highlighted that 10,426 required re-intervention, of which 2.6% (1,251 of 47,474) required endodontic treatment (Burke and Lucarotti, 2009a). More recent studies reported in the literature highlighted re-intervention for all-ceramic crowns requiring endodontic treatment of 4% (9 of 205), 2.5% (34 of 1335) and 8.6% (19 of 219) for five (Ortorp *et al*., 2012), 8.5 (Beier *et al*., 2012) and seven (Rinke *et al*., 2015) year follow-up time intervals.

While seemingly low incidences of re-intervention are reported it has been postulated that the actual incidences of pulpal complications may be under-recorded when determination has been made through clinical assessment only (Burke and Lucarotti, 2009a) and not established through radiographical evidence (Saunders and Saunders, 1998). Saunders and Saunders (1998) reported a conspicuously high incidence (19%) of pulpal complications for periapical radiographs in 87 of 458 crowned teeth, emphasising the asymptomatic potential of pulpal complications. Estimates suggest that 20-50% of NSRCT is performed through dental crowns

(Goldman *et al*., 1992). A survey (Trautmann *et al*., 2000a) of 543 dental practitioners (endodontists, prosthodontists and general practitioners), highlighted that 72% choose to gain access to the pulp chamber through existing crowns and maintain it as a permanent restoration, rather than remove the crown (17%) or place a temporary crown (11%).

The ‘gold standard’ of care for patients requiring a dental crown has traditionally been a porcelain fused to metal (PFM) restoration (Christensen, 2011, Christensen, 2014). Metal-free restorations are increasingly being prescribed in response to patients demands for increased aesthetic appeal and improvements in mechanical properties are responsible for the extended use of all-ceramics to posterior restorations (Brunton *et al*., 1999, Christensen, 2011, Zhang *et al*., 2013). NSRCT through all-ceramic crowns is predicted to increase (Christensen, 2011) however, providing endodontic care through all-ceramic crowns *in situ* is a particular challenge with regard to crown perforation given the current availability of high toughness all-ceramic materials (Lithium disilicate, Alumina, Zirconia). Ceramics are brittle materials and their fracture toughness is flaw dependent (Thompson *et al*., 1994). Flaws such as microcracks can be present as a result of processing or induced by the operator from grinding with sharp tools such as diamonds with potentially detrimental implications for the mechanical properties of the restoration. Isolation of the key factors which influence the fracture resistance of endodontically accessed and repaired all-ceramic crowns are of critical importance for the maintenance of the crown as a permanent restoration and warrant investigation. Access cavity repair is routinely performed using a RC (Trautmann *et al*., 2000b), which is based on maintaining the crown as a permanent restoration, also ensuring a coronal seal and reducing microleakage.

The current systematic review followed and adapted the ‘Preferred Reporting Items for Systematic Review and Meta-Analysis’ (PRISMA) guidelines for reporting systematic reviews that evaluate healthcare interventions (Moher *et al*., 2009) to identify and evaluate the *in vitro* scientific literature to address the focused questions;

1) Which treatment factors influence the fracture resistance of endodontically accessed and repaired all-ceramic crowns? and
2) What is the reported evidence of damage around the endodontic access cavity as a result of preparing the cavity in an all-ceramic crown?

3.2 Materials and Methods

3.2.1 Search Methodology

Medical Subject Heading's (MeSH's) were selected and refined to develop the electronic search concept; endodontic* OR root canal treatment* OR RCT AND access OR cavity AND ceramic* OR porcelain*. The search was customised (Table 3.1) and applied to suit the electronic databases of PubMed/Medline (PubMed, www.ncbi.nlm.nih.gov), Web of Science, Scopus and Embase. No language or date restrictions were applied. A backward and forward author search was carried out for all authors listed on studies forwarded to second round screening, the reference lists of these studies were hand searched for potentially relevant articles. The grey literature (Open Grey) was also consulted. The last search for all databases was run on July 18th, 2016.

Database	Search methodology
Pubmed (1945-)	(endodontic* [All Fields] OR root canal treatment* [All Fields] OR RCT [All Fields]) AND (access [All Fields] OR cavity [All Fields]) AND (ceramic* [All Fields] OR porcelain* [All Fields])
Web of Science (1945-)	Topic (endodontic* OR root canal treatment* OR RCT) AND Topic (access OR cavity) AND Topic (ceramic* OR porcelain*)
Scopus (2008-)	TITLE-ABS-KEY (endodontic* OR root canal treatment* OR RCT) AND TITLE-ABS-KEY (access OR cavity) AND TITLE-ABS-KEY (ceramic* OR porcelain*)
Embase (1990-)	(endodontic* OR root canal treatment* OR RCT) AND (access OR cavity) AND (ceramic* OR porcelain*)
OpenGrey	endodontic* OR root canal treatment* OR RCT AND access OR cavity AND ceramic* OR porcelain*

Table 3.1. Database and search methodology.

3.2.2 Study Selection

The titles and abstracts of all articles identified by the electronic search were read and assessed by two authors (CG, NR). The full text was retrieved where the title and abstract were deemed ambiguous or when no abstract was available. First round exclusion criteria was applied to all articles which were unrelated to endodontics, or dental crowns, which had undergone an endodontic procedure *prior* to placing a restoration, cohort studies, patents, animal studies and conference proceedings. Articles which met the first round inclusion criteria were retrieved in full and reviewed further according to the second round inclusion criteria. The second round screening process excluded supposition articles, surveys, reviews, *in vivo* studies, articles which, concerned the endodontic access of crown types other than all-ceramic, finite element analysis (FEA), studies which involved non-anatomical shaped samples and studies which investigated microleakage.

3.2.3 Data Extraction

Details from the articles included in the systematic review were extracted (when available) by one author (CG) and checked by a second author (NR). Any potential conflict was resolved by discussion with a third author (FB).

3.2.4 Study quality assessment

A risk of bias was assessed using an adaptation of the methods used in two previous systematic reviews of *in vitro* studies (Sarkis-Onofre *et al*., 2014, Rosa *et al*., 2015). Descriptions of the following parameters were used to assess each articles risk of bias: presence of a control group, blinding of the examiner, statistical analysis, evaluation of the access cavity for damage *prior* to repair, use of samples with similar dimensions and access cavity performed by the same operator. Where the parameter was reported, it was assigned a ‘Yes’ and if the information was absent, it was assigned a ‘No’. Articles were classed as having a high risk of bias if one or two parameters were reported, a medium risk if three or four items were reported and a low risk if five or six items were reported. Two authors (CG, NR) independently assessed the methodological quality of each included study and the third author (FB) checked the assessment.

3.3 Results

The PRISMA flow diagram provides an overview of the selection process (Figure 3.1). The electronic search identified 383 articles: 190 from PUBMED/Medline, 142 from Web of Science, 38 from Scopus, and thirteen from Embase. Further analysis revealed 140 duplicate records which were discarded. As a result 243 articles remained, the titles and abstracts of which were screened for first round inclusion. From these 221 were deemed irrelevant and discarded. After first round screening 22 articles remained, the reference lists of these articles were hand searched and a further four studies were identified. Therefore, a total of 26 articles were retrieved in full text and forwarded for second round screening. Eighteen studies were excluded from the analysis after this point (Figure 3.1). Consequently, eight studies formed the basis of this systematic review and the characteristic details extracted (when available) from the articles included in the final study are summarised in Table 3.2. The grey literature (OpenGrey) yielded no new information relevant to the topic, no new articles were identified from the backward and forward author search.

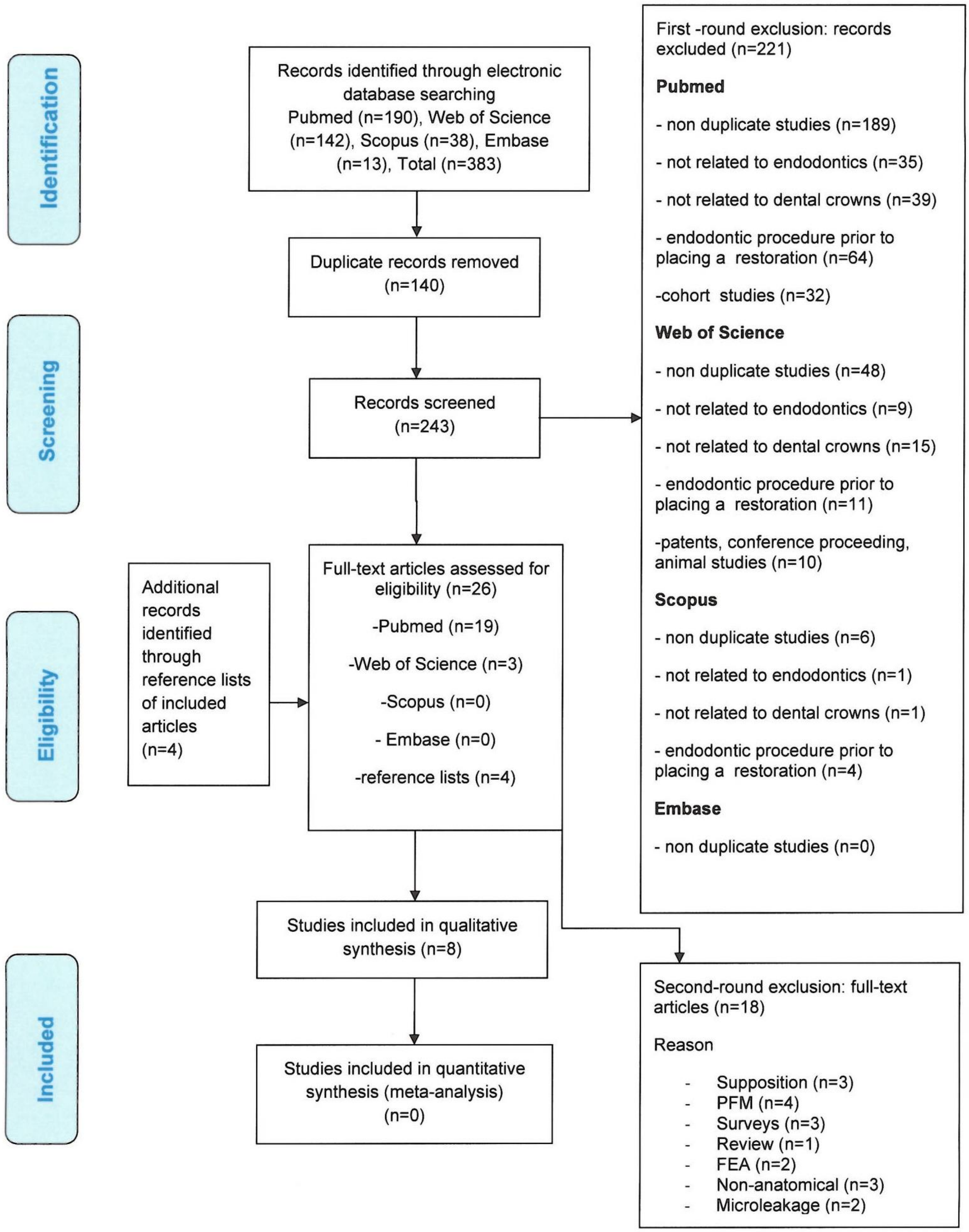

Figure 3.1. PRISMA flow diagram outlining the study identification and screening process.

Authors	Total number of samples in study (n)	Tooth type	All-ceramic crown material	Ceramic processing technique	Die replica substrate	Luting agent	Bur type	Access cavity dimension	Access cavity repair material	Failure load (N) recorded from compression testing	Contact position with load indenter	Reported evidence of damage around the access cavity	Catastrophic crown failures during preparation
Teplitsky and Sutherland 1985	56	Mixed	Alumina core + veneer	Heat pressed+ sintered	Extracted teeth	Temporary cement	Diamond (N=52) Carbide (N=4)	Not specified	N/A	N/A	N/A	Chips, roughness, vague Cracks 1.8% (1/56) at access opening	0 crowns fractured
Stokes et al 1988	30	Incisor-maxillary central	Alumina	Sintered	Metal die	Glass Ionomer cement	Diamond	Triangular 3mm²	Silux resin composite	Control (487.07 ± 10.22) (n=10) Access cavity repaired with composite repair (359.05 ± 118.37) (n=10) Access cavity repaired with silane and composite repair (354.14 ± 58.4) (n=10)	Incisopalatal-on ceramic only	Not reported	Not reported
Sutherland et al 1989	42	Mixed	Fluoromica	Cast	Extracted teeth	Temporary cement	Diamond or carbide, vague	Not specified	N/A	N/A	N/A	Craze lines 17% (7/42), chipping 69% (29/42)	2 crowns fractured (4.8%)
Cohen and Wallace 1991	6	Mixed	Fluoromica	Cast	Extracted teeth	Zinc phosphate (n=3) Polycarboxylate (n=3)	Diamond	Not specified	N/A	N/A	N/A	Chipping at access cavity, vague, not quantified	1 crown fractured (17%)
Haselton et al. 2000	28	Premolar	Leucite	Heat pressed	Extracted teeth	Dual-cure resin cement (Variolink)	Diamond (n=14) or Tungsten carbide (n=14)	Not specified	N/A	N/A	N/A	Edge chipping 100% (28/28) Microcracks 14% (4/28) Fractures 11% (3/28)	3 crowns fractures (11%)
Wood et al 2006	48	Molar-standardised	Zirconia core + ceramic veneer (n=24)	CAD CAM + heat pressed CAD CAM + heat pressed	Epoxy resin	Resin modified glass-ionomer (Rely X Luting Plus cement)	Diamond	3.5 mm round diameter	XRV Herculite resin composite	Alumina intact (1410 ± 111) (n=12), $m = 12.8$ Alumina repaired (1436 ± 223) (n=12), $m = 6.2$ Zirconia intact (2432 ± 181) (n=12), $m = 13.4$	Axial- on ceramic and resin repair	Irregularities Edge chipping 100% (Zirconia) Radial cracks-Zirconia (4/24)	Not reported

			Alumina core + ceramic veneer (n=24)							Zirconia repaired (2075 ± 348) (n=12), m = 5.4		Edge chipping 100% (Alumina)	
Qeblawi et al 2011	60	Molar- maxillary first	Lithium disilicate	Heat pressed	Resin composite	Dual polymerising resin (Multilink Implant) or Zinc phospahate (Flex's)	Diamond (126 µm, 150 and 180 µm grit size)	Not specified	Tetric Evo Ceram resin composite	Luted with DPR* intact crown (3316 ± 483) (n=10) Luted with DPR, access cavity prepared with 126µm grit diamond bur (3464 ± 645) (n=10) Luted with DPR, access cavity prepared with 150µm grit diamond bur (2915 ± 569) (n=10) Luted with DPR, access cavity prepared with 180µm grit diamond bur (2354 ± 476) (n=10) Luted with ZP** intact crown (2242 ± 369) (n=10) Luted with ZP, access cavity prepared with126µm grit diamond bur (1999 ± 448) (n=10)	Axial- on ceramic only	Not reported	Not reported
Bompolaki et al 2015	40	Molar- standardised	Lithium disilicate	Heat pressed (n=20) Milled (n=20)	Epoxy resin	Dual-cure resin cement (Variolink II)	Diamond (126 µm grit size)	3.5 mm round diameter	Filtek Supreme resin composite	Pressed intact (1901 ± 349) (n=10), m = 5.9 Pressed repaired (1429 ± 384) (n=10), m = 3.9 Milled intact (1573 ± 267) (n=10), m = 6.3 Milled repaired (1297 ± 329) (n=10), m = 4.5	Axial- on ceramic and resin repair	Edge chipping 100% (pressed) (4/4) Edge chipping 100% (milled) (4/4) Radial crack 25% (milled) (1/4)	Not reported

m Weibull modulus, * Dual polymerised resin, ** Zinc phosphate cement

Table 3.2. Characteristic details of the studies included in the current review (Teplitsky and Sutherland, 1985, Stokes *et al*., 1988, Sutherland *et al*., 1989, Cohen and Wallace, 1991, Haselton *et al*., 2000, Wood *et al*., 2006, Qeblawi *et al*., 2011, Bompolaki *et al*., 2015).

3.3.1 Study quality assessment

Of the eight studies included, three presented a high, two a medium and three a low risk of bias (Table 3.3). The studies scored particularly poorly in relation to blinding of the examiner. None of the eight studies included a statement which denied conflicts of interest.

3.3.2 Repair protocols

Protocols and materials used to repair the access cavity were reported in four articles (Table 3.4). No significant ($p<0.001$) difference was found in failure load with variation (inclusion of silane) in the protocol (Stokes et al., 1988).

Authors	Control group	Blinding of the examiner	Statistical analysis carried out	Evaluation of the access cavity for damage	Samples with similar dimensions	Endodontic access cavity performed by a single operator	Risk of Bias
Teplitsky and Sutherland (1985)	No	No	No	Yes	No	No	High
Stokes et al (1988)	Yes	No	Yes	No	Yes	No	Medium
Sutherland et al (1989)	No	No	No	Yes	No	No	High
Cohen and Wallace (1991)	No	No	No	Yes	No	No	High
Haselton et al. (2000)	Yes	No	Yes	Yes	Yes	Yes	Low
Wood et al (2006)	Yes	No	Yes	Yes	Yes	Yes	Low
Qeblawi et al (2011)	Yes	No	Yes	No	Yes	No	Medium
Bompolaki et al (2015)	Yes	No	Yes	Yes	Yes	Yes	Low

Table 3.3. Quality assessment and risk of bias of the eight included studies (Teplitsky and Sutherland, 1985, Stokes *et al*., 1988, Sutherland *et al*., 1989, Cohen and Wallace, 1991, Haselton *et al*., 2000, Wood *et al*., 2006, Qeblawi *et al*., 2011, Bompolaki *et al*., 2015).

Authors	Etchant	Etch time	Silanation	Primer	Intermediary resin layer	Repair resin composite	Curing technique	Finishing technique	Storage
Stokes et al (1988)	Phosphoric acid gel (% not specified)	1 min	Scotchbond n=10	Scotchbond+ scotchprime n=10	Not specified	Silux composite resin (3M Co St Paul, MN, USA)	Not specified	Not specified	Tested immediately
Wood et al (2006)	4% HFL	4 min	Porcelain silane primer- 2 min, air dry	All-bond 2 primer A&B – 5 coats, air dried	Porcelain bonding resin, air thin and light cure	XRV Herculite Unidose hybrid composite resin (Kerr Corp, Orange, California, USA)	2 increments light cured for 40 sec each	1200 grit silicon carbide paper	Saline 24 hr
Qeblawi et al (2011)	4.5% HFL (IPS ceramic etch gel)	20 sec	Monobond Plus-1 min	Not specified	Not specified	Tetric evoceram (Ivoclar Vivadent AG)	2 increments light cured for 20 sec each	Not specified	Incubator-1 week, then, after repair stored again-1 week
Bompolaki et al (2015) *	9.5% HFL (sandblast or roughen surface with diamond bur as alternative)	90 sec	Porcelain primer	Not specified	Porcelain bonding resin and light cure	Filtek supreme ultra universal restorative (Ultra Universal Restorative; 3M ESPE)	Not specified	Rubber wheel under water irrigation	Saline-3 weeks, then fatigued with dry cyclic load prior to testing

*Authors referred to the use of Bisco inc, intraoral repair kit but not specify the exact procedures which were carried out

Table 3.4. Details of the repair protocols used for the restoration of endodontic access cavities in all-ceramic crowns (Teplitsky and Sutherland, 1985, Stokes et al., 1988, Sutherland et al., 1989, Cohen and Wallace, 1991, Haselton et al., 2000, Wood et al., 2006, Qeblawi et al., 2011, Bompolaki et al., 2015).

3.3.3 Access cavity instrumentation

Access cavity dimensions were varied (Teplitsky and Sutherland, 1985, Stokes *et al*., 1988, Sutherland *et al*., 1989, Cohen and Wallace, 1991, Haselton *et al*., 2000, Wood *et al*., 2006, Qeblawi *et al*., 2011, Bompolaki *et al*., 2015) (Table 3.2). Diamond burs (Teplitsky and Sutherland, 1985, Stokes *et al*., 1988, Sutherland *et al*., 1989, Cohen and Wallace, 1991, Haselton *et al*., 2000, Wood *et al*., 2006, Qeblawi *et al*., 2011, Bompolaki *et al*., 2015) were the instrument of choice for creating access cavities rather than carbide burs which were found to be ineffective (Teplitsky and Sutherland, 1985, Sutherland *et al*., 1989) in all but one (Haselton *et al*., 2000) where no difference ($p>0.05$) was reported. A large diamond grit size (150-180 µm) bur significantly ($p< 0.05$) lowered the mean load to failure of endodontically accessed lithium disilicate crowns (Qeblawi *et al*., 2011). Descriptive details of the damage around the access cavity are given in Table 3.2. Radial cracks were noted in two studies (Wood *et al*., 2006, Bompolaki *et al*., 2015), a correlation was made between 75% (n=4) of samples which exhibited radial cracks prior to repair and the lowest recorded failure loads (Wood *et al*., 2006). An increased risk of crown fracture during access preparation was noted (Sutherland *et al*., 1989, Cohen and Wallace, 1991, Haselton *et al*., 2000), up to 50% of mandibular incisor fractures (Sutherland *et al*., 1989) occurred during access cavity preparation.

3.3.4 Failure load

The failure load (Table 3.2) of intact crowns compared with those which had an access cavity drilled and restored, was found to be uninfluenced by, variation in the repair protocol (Stokes *et al*., 1988) and influenced by the, type of ceramic crown material (Wood *et al*., 2006), diamond grit size of the bur (Qeblawi *et al*., 2011), luting agent (Qeblawi *et al*., 2011) and method of crown fabrication (Bompolaki *et al*., 2015). Sample storage, ageing and loading conditions varied considerably between these four studies (Table 3.4). Wood *et al*. (2006) noted three instances (n=12) where the substrate material failed before fracture of the intact zirconia crown. Combined failure of both crown (lithium disilicate) and die replica substrate (Tetric Evo Ceram, Ivoclar) was reported for 50% of all samples (n=60) in the study at failure loads of 2915 ± 569 N or higher (Qeblawi *et al*., 2011). A linear relationship between failure load (2354 ± 476 N, 2242 ± 369 N and 1999 ± 448 N) and the percentage of combined ‘crown and substrate’ failures (60%, 50% and 30%) was evident, ‘crown only’ failures were reported at lower failure loads (Qeblawi *et al*., 2011). While various luting agents (Table 3.2) were used in each study, one study investigated its influence as a variable on the failure load (Qeblawi *et al*., 2011). Whilst none of the studies investigated retention of the accessed and repaired restoration, Cohen and Wallace (1991) observed loss of retention for 100% (n=3) of fluoromica crowns cemented with zinc phosphate cement after NSRCT was performed.

3.4 Discussion

The objective of the current systematic review was to elucidate from *in vitro* studies, which treatment factors employed to perform an endodontic access cavity, and its repair in an all-ceramic crown influenced the fracture resistance of the crown. The relatively few publications (n=26) identified from 1962-2016 was surprising given the frequency (Goldman *et al*., 1992, Trautmann *et al*., 2000a) with which the clinical procedure is carried out. Eight articles (1985-2015) were selected which purported to address the focus questions however, only three scored a low risk of bias according to the study quality assessment criteria used. Systematic reviews of *in vitro* literature are becoming more commonplace (Faggion, 2012), this has led to the identification of a clear lacuna in the literature in relation to the standard of reporting for *in vitro* studies, no evidence of validated checklists or guidelines exist (Faggion, 2012, Krithikadatta *et al*., 2014).

The results of this systematic review highlighted the growth and improvements in the mechanical properties of all-ceramic dental crown materials which has taken place over the past three decades. Arguably, the age profile of some of the included studies may restrict the relevance to contemporary clinical practice particularly in relation to current material options. Improved material properties offer increased resistance to crack propagation but are concomitant with increased difficulty in performing surface adjustments with rotary instruments. Machining modern dental ceramic materials with sharp tooled instruments is necessary (for example) for, manufacturing (CAD/CAM), adjustments to improve restoration fit in the clinic or laboratory and, clinical procedures involving, minor adjustments to contacts or, significant alterations such as drilling an endodontic access cavity *in situ*. Operational parameters, such as cutting speed and pressure have been linked with surface flaws and coexistent subsurface damage in dental ceramics (Song and Yin, 2009). In the current systematic review, surface damage was evident through microcracks and edge chipping localised to the endodontic access cavity (Teplitsky and Sutherland, 1985, Sutherland *et al*., 1989, Cohen and Wallace, 1991, Haselton *et al*., 2000, Wood *et al*., 2006, Bompolaki *et al*., 2015). It was not possible to make quantitative comparisons of the damage observed across the studies included in the review since terms such as craze lines, chipping, microcracks, irregularities, roughness were ill defined, used interchangeably and applied loosely for the outcomes observed (Teplitsky and Sutherland, 1985, Sutherland *et al*., 1989, Cohen and Wallace, 1991) or not inspected at all (Stokes *et al*., 1988, Qeblawi *et al*., 2011). The flaw dependent (Thompson *et al*., 1994) properties of dental ceramics are major restrictions to their wider intraoral use, since the presence of microcracks serve to act as stress concentrators which may contribute to catastrophic clinical failure (Rekow and Thompson, 2007). The susceptibility of ceramic materials to static fatigue intraorally (Ritter, 1995, Jung *et al*., 2000) further exacerbates the situation.

While the high incidence of endodontic treatment (Goldman *et al*., 1992) after crown placement render it a routine clinical procedure (Trautmann *et al*., 2000a), the findings of the current review indicate that, *in vitro* studies to inform clinical repair protocols relating to the fracture resistance of endodontically accessed and repaired all-ceramic restorations are scant. One study addressed variation in the repair protocol (inclusion of silane) which produced no significant increase in the fracture resistance of the accessed and repaired crown (Stokes *et al*., 1988). However, it is worth noting that the standard deviation for failure load approximately halved for this group which may suggest an improvement in the 'reliability' of mechanical properties with this intervention. Broader variations in repair protocols are worthy of further investigation.

While acid etching to promote the adhesion of resin to glass-ceramics is a routine step in the process (Zhang and Degrange, 2010), the intraoral use of aqueous hydrofluoric acid remains controversial due to its hazardous nature (Kimmich and Stappart, 2013). Silane coupling agents mediate strong chemical bonding between glass-ceramics and RC's as they increase the reactivity of the surface layer in the glass-ceramic forming a siloxane network while co-polymerising the organic matrix of the RC (Luthra and Kaur, 2015). Polycrystalline ceramics such as Zirconia are resistant to acid attack, various surface treatments including, alumina particle abrasion, selective infiltration etching and tribochemical coating have been tried with varying degrees of success to promote adhesion (Tzanakakis *et al*., 2016). Evidence now exists to demonstrate that successful bonding with Zirconia can be obtained using resins in conjunction with phosphate acid ester monomers (MDP), however initially high bond strengths are not maintained with artificial aging (DeSouza *et al*., 2014). For this reason the prevention of microleakage in endodontically accessed and repaired oxide ceramic crowns may be unpredictable.

Lack of an adhesive cement layer between the tooth and a zirconia crown may give rise to reduced crown retention as a consequence of access cavity preparation, similar to that which was noted in one study (Cohen and Wallace, 1991) and also shown with metal ceramic crowns (McMullen *et al*., 1989, McMullen *et al*., 1990). No rationale was given for the RC's selected to repair the access cavity (Stokes *et al*., 1988, Wood *et al*., 2006, Qeblawi *et al*., 2011, Bompolaki *et al*., 2015), conjecture might suggest that selection was based on convenience and availability. Important properties should include wear resistance, MOE and flowability to promote a sufficiently strong repair in addition to an excellent seal with the all-ceramic restoration.

Four articles in the current study repaired the endodontic access cavity with RC and reported failure load values as a measure of fracture resistance. Two studies concluded that the repair could 'restore the strength' (Wood *et* *al*., 2006, Bompolaki *et al*., 2015) of the original restoration. However, it was not established that the RC was responsible for this outcome since none of the studies (Stokes *et al*., 1988, Wood *et al*., 2006, Qeblawi *et al*., 2011, Bompolaki *et al*., 2015) included a control (unrestored cavity) for this in the protocol. Despite a significant difference in failure load for the intact zirconia crowns versus the accessed and repaired zirconia crowns, the latter group reported higher failure loads compared with intact alumina crowns (Wood *et al*., 2006). This concurs with other researchers which have concluded that the baseline material strength is the most significant influencing factor for the resistance to fracture of a crown (Rekow and Thompson, 2007). Despite failure loads (Bompolaki *et al*., 2015) which indicated that accessed and repaired crowns could provide potentially serviceable restorations with long term prognosis, the dramatic reduction in Weibull modulus (Table 3.2) cannot be ignored. The negative influence of increased grit size (150-180µm) of the diamond bur on the failure load recorded was a noteworthy clinical consideration, however the lack of micrographic investigation in the study limited further interpretation of the data (Qeblawi *et al*., 2011). Choice of luting agent in this study also impacted on the fracture resistance where adhesive cementation was associated with higher failure loads. Adhesive compared with conventional cementation has been shown to increase the load bearing capacity of glass-ceramic crowns (Qeblawi *et al*., 2011, Burke *et al*., 2002).

Wood *et al*. (2006) suggested that the presence of radial cracks after the preparation of the access cavity should be a deciding factor whether to abandon the repair and remake the crown since their presence were strongly correlated with lower failure loads. Catastrophic crown failures reported during the access cavity preparation (Sutherland *et al*., 1989, Cohen and Wallace, 1991, Haselton *et al*., 2000), could be synonymous with the low toughness of the materials used (fluoromica and leucite glass-ceramics) compared with more recently available ceramics (lithium disilicate, alumina and zirconia) with higher toughness (between 3 and 12 $MPa.m^{0.5}$) (Wood *et al*., 2006, Qeblawi *et al*., 2011, Bompolaki *et al*., 2015). The increased ratio of access cavity to crown size in mandibular incisors (Sutherland *et al*., 1989) could reasonably explain the 50% failure rate observed.

Large differences in failure load for intact (3316 ± 483 N versus 1573 ± 267 N) and accessed (with 126 µm diamond grit bur) and repaired cavities (3464 ± 645 N versus 1297 ± 329 N) in lithium disilicate crowns reported in two studies (Qeblawi *et al*., 2011, Bompolaki *et al*., 2015, respectively) may be attributed to variances in the experimental methodology applied for ageing and storing samples prior to testing and also the different contact positions made with the load indenter. There is no consensus in the literature with regard to artificial ageing regimes, various recommendations have been proposed to induce failure loads and fracture patterns within a clinically meaningful range (Kelly, 1999, Jung *et al*., 2000, Kelly *et al*., 2010, Rekow *et al*., 2011). The combined crown and die replica substrate fractures occurring at high failure loads was attributed (Qeblawi *et al*., 2011) to the low modulus of elasticity (approximately 10 GPa) of the die replica substrate material. The modulus of elasticity of the substrate on which a restoration is placed has been shown to influence its structural performance (Scherrer and de Rijk, 1993, Wang and Darvell, 2012).

The high heterogeneity of the included studies rendered it impossible to carry out quantitative analyses of the data. The need for long term clinical data concerning the survival of endodontically accessed all-ceramic crowns previously identified (Teplitsky and Sutherland, 1985, Sutherland *et al*., 1989) is also endorsed by the authors of this systematic review.

3.5 Conclusion

There is currently no scientific evidence to recommend a ‘best practice’ clinical protocol to maximise fracture resistance in repaired all-ceramic crowns which have been accessed for endodontic treatment. The paucity of existing evidence from the scientific literature would advise cautious interpretation for clinical purposes of the following potentially influential factors.

1) The material and its adhesive potential, from which the crown has been made i.e. glass-ceramic or polycrystalline ceramic.
2) The initial baseline material strength from which the crown is made.
3) Whether the crown has been adhesively or non-adhesively cemented to the tooth.
4) The diamond grit size of the bur selected to create the access cavity.
5) Evaluation of the access cavity *after* preparation (remake the crown if severe defect i.e. radial cracking, is apparent)
6) The ratio of access cavity to crown size.

- Randomised controlled trials, retrospective and prospective studies addressing this topic are warranted to inform survival probabilities in a clinical setting.

Chapter 4

Equibiaxial flexural strength determination of Lithium Disilicate glass-ceramic substrates with simulated endodontic access cavities - Impact of cavity dimension and repair material

This chapter is under peer review as;

Equibiaxial flexural strength determination of Lithium Disilicate glass-ceramic substrates with simulated endodontic access cavities - Impact of cavity dimension and repair material

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Abstract

Objectives: To evaluate the effect of access cavity dimension and modulus of elasticity of resin composite repair material on the mean equibiaxial flexural strength (EBFS) of lithium disilicate glass-ceramic (LDGC) disc substrates with representative endodontic access cavities.

Methods: 210 lithium disilicate discs were divided into seven groups. Group A (control), Groups B, C, D (3 mm access cavity) and Groups E, F, G (5 mm access cavity). The Groups were treated as follows; the access cavity was either, unfilled (Group B and E) or, primed and silanated then filled with, low modulus of elasticity resin composite (Group C and F), or high modulus of elasticity resin composite (Group D and G). The discs were subjected to thermocycling and water storage prior to EBFS testing. A one-way and two-way analysis of variance (ANOVA) statistical analysis was carried out to compare group means at $p < 0.05$, Tukey HSD post hoc analysis was performed. The Weibull moduli of each group was also determined.

Results: Mean EBFS values for Group A were significantly higher than all other groups. The effect of cavity preparation and dimension on the EBFS was significant, the repair of access cavity was not significant and the modulus of elasticity of repair material was not found to be significant. A cavity-repair interaction effect was identified.

Conclusions: Within the limitations of the experimental protocol, the introduction of representative endodontic access cavities in lithium

disilicate glass-ceramic disc substrates significantly reduced the mean EBFS. An increased dimension of access cavity produced a significant decrease in EBFS. The repair of the access cavity with resin composite or the choice of resin composite repair material did not increase the EBFS.

Clinical significance: The presence of an endodontic access cavity in a lithium disilicate glass-ceramic material significantly reduced the EBFS compared with the intact equivalent. However, the reduced EBFS values obtained for the accessed specimens may be comparable to some intact, but weaker glass-ceramic restorative materials.

4.1 Introduction

Clinical demand for all-ceramic restorations have increased due to patient response for optimum aesthetics combined with improved mechanical properties of modern ceramic materials (Brunton *et al*., 1999, Pagniano *et al*., 2005, Christensen, 2011, Zhang *et al*., 2013, Zarone *et al*., 2016, Clavijo *et al*., 2016). However, the cumulative effects of tooth preparation and crown provision are recognised as a significant contributing factor to pulpal necrosis (Dahl, 1977, Bergenholtz, 1991, Christensen, 1997, Trautmann *et al*., 2000a, Edelhoff and Sorenson, 2002, Christensen, 2005). Incidences of between 2.1%-8.6% (Goodacre *et al*., 2003, Pjetursson *et al*., 2007, Burke and Lucarotti, 2009b, Ortorp *et al*., 2012, Beier *et al*., 2012, Rinke *et al*., 2015) are reported for crowned teeth which required subsequent endodontic treatment when determined through clinical assessment alone. Higher incidences (19%) were reported with radiographic assessment (Saunders and Saunders, 1998).

Goldman *et al*., (1992) estimated that, endodontic access to the pulp chamber is achieved by crown perforation *in situ* in 20-50% of cases. A preference was reported amongst dental practitioners (72% of 543), to provide endodontic treatment through pre-existing crowns (Trautmann *et al*., 2000a). Resin composite was the most frequently (70.6%) chosen material to repair the access cavity in all-ceramic crowns (Trautmann *et* *al*., 2000b).

Obtaining endodontic access through all-ceramic crowns is a substantial challenge given the high toughness of modern all-ceramic dental materials (Christensen, 2011). A recent systematic review highlighted the limited research which this problem has commanded to date in the dental literature, with some 26 articles identified over a 54-year period (1962-2016), few of which consisted of high quality *in vitro* studies (Gorman *et al*., 2016). The literature has not reported the many issues (biological, mechanical, physical, financial) surrounding the endodontic treatment of teeth when all-ceramic dental restorations are *in situ*.

Previous *in vitro* studies used load to failure tests to report that, the failure load of all-ceramic crowns which had been endodontically accessed can be regained once a resin composite repair of the cavity had been made (Stokes *et al*., 1988, Wood *et al*., 2006, Qeblawi *et al*., 2011, Bompolaki *et al*., 2015). However, the failure load of crowns with an unrestored access cavity was not determined and therefore the evidence was inconclusive. Of particular relevance to the current study are two studies which investigated the biaxial flexure strength of flat disc specimens for two glass-ceramic restorative materials (feldspathic and leucite) with and without representative access cavities but the flexure strength of discs with repaired access cavities was not established in the investigation (Kelly *et al*., 2014, Kelly *et al*., 2017). Decreased Weibull moduli (reliability) were reported for specimens which had an endodontic intervention for all-ceramic crowns (Wood *et al*., 2006, Bompolaki *et al*., 2015) and discs (Kelly *et al*., 2014, Kelly *et al*., 2017) when compared with their intact equivalents. Leucite disc specimens coated with a thin layer of resin composite (to represent adhesive cementation), demonstrated an increased Weibull modulus, this was attributed to ceramic reinforcement via interaction between the resin and surface flaws in the ceramic (Kelly *et al*., 2017). A resin-ceramic hybrid layer has been correlated with an increase in flexure strength for glass-ceramic materials (Pagniano *et al*., 2005, Addison *et al*., 2008). A linear relationship between the modulus of elasticity of resin composite luting cement and ceramic flexure strength has been demonstrated (Addison *et al*., 2007). The positive influence of a resin composite cement layer on flexure strength was demonstrated for feldspathic but not leucite, glass-ceramic discs with simulated endodontic access cavities (Kelly *et al*., 2017). Similarly, significantly higher failure loads were reported for all-ceramic crowns with endodontic access cavities when luted with resin as opposed to zinc phosphate cement. However, a corresponding increase in Weibull modulus was not observed (Qeblawi *et al*., 2011).

Diamond rotary instruments with a coarse grit size (150–180 µm) significantly reduced ($p < 0.05$) the failure load of endodontically accessed all-ceramic lithium disilicate glass-ceramic (LDGC) crowns compared with standard (126 µm) diamond grit sized burs (Qeblawi *et al*., 2011). The machining of endodontic access cavities in all-ceramic crowns demonstrated appreciable damage, described as chipping and microcracking at the access cavity for a broad range of all-ceramic restorative materials (Teplisky and Sutherland, 1985, Sutherland *et al*., 1989, Cohen and Wallace, 1991, Haselton *et al*., 2000, Wood *et al*., 2006, Beck *et al*., 2010, Kelly *et al*., 2014, Bompolaki *et al*., 2014, Kelly *et al*., 2017). The extent of damage may be underreported since it is reliant on the sensitivity of the light source employed for detection (Sabourin *et al*., 2005, Beck *et al*., 2010). Flaws are detrimental to the mechanical properties since they act to concentrate stress in an area from which failure can occur, particularly in an environment where moisture and antagonistic loading are inevitable (Ritter, 1995, Jung., 2000, Lawn *et al*., 2001). *In vitro* attempts to simulate the effect of temperature fluctuation in a moist environment involve ageing regimes with thermocycling which are reported to improve the clinical relevance of data obtained (Kelly, 1999, Jung *et al*., 2000, Kelly *et al*., 2010, Rekow *et al*., 2011), however no agreed standard for thermocycling exists (Gale and Darvell, 1999).

LDGC is among the most popular contemporary all-ceramic dental restorative materials commercially available (Pagniano *et al*., 2005, Della

Bona and Kelly, 2008, Valenti and Valenti, 2009, Zarone *et al*., 2016) and advocated for multiple restorative solutions across all areas of the oral cavity (Ivoclar Vivadent, 2014). LDGC is a high strength glass-ceramic with excellent optical and mechanical properties. Flexural strengths between 213.8 MPa and 440 MPa have been reported in the literature (Albakry *et al*., 2003, Pagniano *et al*., 2005). Different test methodologies (3 or 4-point bend and biaxial flexure tests), aging protocols and surface finish can account for wide variation in reported measures of strength observed across studies (Kelly, 1995, Giordano *et al*., 1995). Clinical adjustments may reduce the strength of a LDGC crown from the ‘as manufactured’ state which may result in intergranular and transgranular fractures of the acicular shaped lithium disilicate (LD) crystals. This effect may be correlated with increased difficulty in machinability compared with, for example, traditional feldspathic glass-ceramics (Song *et al*., 2016). Preparation of an endodontic access cavity in an all-ceramic crown *in situ* is arguably the most extreme clinical ‘adjustment’ a crown is likely to be subjected to, thereby testing the limits of the materials properties.

Increased access cavity to crown ratio has been suggested as a factor associated with the observed increase in risk of catastrophic crown failure (Sutherland *et al*., 1989, Cohen and Wallace, 1991, Haselton *et al*., 2000). Higher access cavity to crown ratios may occur when, additional root canals are present and root location cannot be easily determined due to morphological differences between the original and restored crown (Gutmann and Fan, 2016). Variations in access cavity design carried out in an finite element analysis (FEA) study determined that elliptical was optimal, compared with a rectangular or double access design and that high curvature cavity boundaries should be avoided (Cuddihy *et al*., 2013). In the current study, simple disc geometries with representative access cavities were used to standardise experimental procedures and permit reliable data collection, while simultaneously ensuring a low access cavity curvature.

The aim of the current investigation was to identify how the access cavity dimension and elastic moduli of a resin composite repair material affected the EBFS of monolithic LDGC disc substrates when tested under monotonic loading in a biaxial mode.

The null hypotheses ae that EBFS is not affected by:

1) The introduction of an endodontic access cavity

2) The repair of an endodontic access cavity,

within the limits of the experimental protocols

4.2 Materials and Methods

4.2.1 Test specimen preparation

210 Lithium disilicate glass ceramic (LDGC) discs were fabricated using the heat-pressed technique. Plastic discs (Gilbert Curry industrial plastics, Coventry CV7 9EJ, England), 15 mm in diameter and 1.5 mm in thickness were invested in a phosphate bonded investment material (IPS PressVest Speed, Ivoclar Vivadent AG, Schaan/Liechtenstein) and the manufacturer's instructions were followed for the burnout, pressing and divesting of the IPS e.max® Press material (Ivoclar Vivadent, 2014). The retrieved specimens were ground flat on both sides using 180 grit SiC paper (Buehler-Met, Lake Bluff, Illinois, USA). Specimen thickness was measured at several intervals around the disc using a digital calliper (Milomex Ltd., Bedfordshire, UK) for parallelism ± 0.05 mm. The average thickness (h) of each specimen was recorded. 30 specimens were randomly assigned to each of seven groups (A-G).

A permanent marker was used to mark the dimension of the representative circular endodontic access cavity (3 mm or 5 mm) in the centre of the disc through a plastic template. An access cavity was prepared with the disc submerged in water using a round 2.3 mm coarse-grit diamond rotary cutting bur (GW801.023 FG, Edenta AG, Switzerland) in a standard laboratory handpiece (Kavo-K9, Kavo, Germany). Each bur was replaced after five uses. The access cavity was extended to the outline of the marker with a standard grit diamond bur (356.316.023FG, Edenta AG, Switzerland). The internal diameter of each cavity was measured to within 0.01 mm using a digital callipers at three equidistant points, the coefficient of variance was determined for each specimen. The drill entry side (top) was marked with an alcohol pen to correspond with the load surface during testing, thereby ensuring that the 'fit' surface would be placed under tension analogous to the clinical scenario.

The disc specimens were cleaned to remove debris using a steam cleaner (Electronic steamer II, Amann Girrbach, 6842 Kobiach, Austria). The access cavity margins were primed with 37% phosphoric acid etchant (Total Etch, Ivoclar Vivadent AG, Schaan/Liechtenstein) for 60 seconds, rinsed with water and dried with a stream of oil free air. A porcelain silane primer (Monobond S primer, Ivoclar Vivadent AG, Schaan/Liechtenstein) was applied to the access cavity margins for 60 seconds and the excess dried with a stream of oil free air. The disc specimen was placed on a mylar matrix strip on a glass microscope slide and the cavity was filled with either, a low modulus of elasticity (LMOE) resin composite for Group C and F (TetricEvoFlow, Ivoclar Vivadent AG, Schaan/Liechtenstein) or a high y of elasticity (HMOE) resin composite for group D and G (Tetric EvoCeram, Ivoclar Vivadent AG, Schaan/Liechtenstein) (Table 4.1). A mylar strip and a glass microscope slide was placed on top of the assembly. Both resin surfaces of each specimen were exposed to a dental light curing unit (Deguluv soft start, Dentsply, UK, 40 secs; nominal irradiance = 800 $mWcm^2$). The specimens were then stored in distilled water for seven days. The specimens were subjected to 500 thermocycles in digitally controlled baths (Thermo Haake DC10-EK30, Digital Control Bath, Germany) and held between 5°C ± 2°C and 55°C ± 2°C with a dwell time of 10 seconds, a drain time of 10 seconds and transfer time of 10 seconds. The specimens were then removed and stored in water at 37°C for a further 14 days.

GROUP	ACCESS CAVITY DIMENSION (MM)	RESIN COMPOSITE REPAIR MATERIAL	RESIN COMPOSITE MODULUS OF ELASTICITY
A	N/A	N/A	
B	3	Unfilled	
C	3	LMOE*	5.1 GPa
D	3	HMOE**	10 GPa
E	5	Unfilled	
F	5	LMOE	5.1 GPa
G	5	HMOE	10 GPa

Table 4.1. Descriptive summary of Groups A-G.
*** LMOE Tetric EvoFlow (Ivoclar Vivadent) ** HMOE Tetric EvoCeram (Ivoclar Vivadent).**

4.2.2 Equibiaxial flexure strength determination

A ring-on-ring test method (ASTM C 1499 – 05, Appendix-Section 9.6) was used to load the discs until failure using a commercially constructed jig (Wyoming test fixtures, UT, USA). Each disc was removed from storage and dried, a piece of clear adhesive tape was placed on the compressive surface (top). The disc was centred on the support ring of the test jig and the loading ring was centred on the disc (Figure 4.1). A thin piece of non-rigid material (polyethylene sheet) was placed between the loading ring and the disc. A paper screen was placed around the testing apparatus to contain the fractured fragments. An incremental force was applied to the test jig using a tensometer (Tinius Olsen H10KS, Tinius Olsen Ltd, Perrywood Business Park, Redhill, Surrey, UK) at a rate of 0.75 mm/min in a compressive mode until the material failed. A 10 kN load-cell was used with a load range of 50%. The load at failure was recorded for each disc and the fragments collected for further examination.

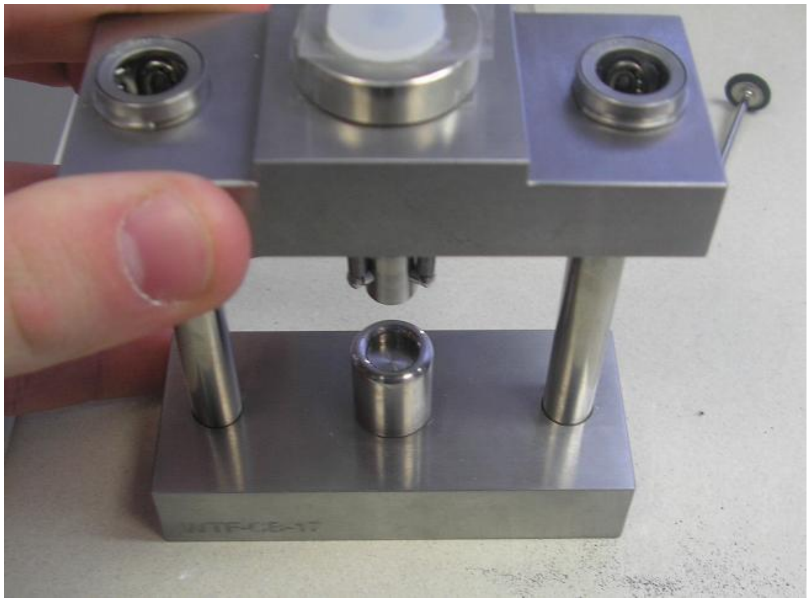


Figure 4.1. The equibiaxial flexural test fixture with concentric ‘ring-on-ring’ support and load rings (ASTM C1499-05).

EBFS was calculated for each specimen using the following equation (ASTM C 1499 – 05);

$$\sigma_f = \frac{3F}{2\pi h^2}\left[(1-v)\frac{D_S^2 - D_L^2}{2D^2} + (1+v)\ln\frac{D_S}{D_L}\right]$$

Where σ_f is the maximum tensile stress (MPa), F is the total load causing fracture (N), h is the specimen thickness at fracture origin (mm), v is the Poisson’s ratio (taken here to be 0.23), D_L is the radius of the load ring (3 mm), D_S is the radius of the support ring (6 mm) and D is the radius of the specimen (7.5 mm).

4.2.3 Statistical Analysis

30 specimens were deemed an appropriate specimen size to identify the summary statistics of the population relating to each group (ASTM C 1499-05, Quinn and Quinn, 2010). Assumptions for ANOVA were tested using Levene's test for homogeneity and Shapiro-Wilkes test for normality. Analyses were performed using R statistical software (version 3.3.3) and corresponding packages: 'fitdistrplus' and 'car' (Delignette-Muller and Dutang, 2015).

A one-way ANOVA analysis was used to determine if there was a difference between all group means. A two-way ANOVA was performed to determine if there was a difference in group mean EBFS between all interventions (i.e. all groups B-G, except the control group A). Post hoc Tukey HSD multiple comparisons of the means were performed using a 95% family-wise confidence level.

The null hypotheses are that EBFS is not affected by:

1) The introduction of an endodontic access cavity

2) The repair of an endodontic access cavity,

within the limits of the experimental protocols.

Weibull statistics (Weibull, 1951) were carried out for the data using the Weibull cumulative probability function given as:

$$Pf = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_\theta}\right)^m\right]$$

Where, Pf = the probability of failure, m = shape parameter (Weibull modulus) and σ_θ = scale parameter (characteristic strength). Maximum likelihood estimation (MLE) was used for parameter estimation, MLE increase the accuracy of confidence intervals compared with linear regression analysis (Quinn and Quinn 2010). The Weibull modulus (m) is reflective of the scatter in the data, the characteristic strength (σ_θ) reflects the mean strength at which 63.2% of specimens will fail. Weibull parameters are considered a useful tool for interpreting data compared with reporting mean and standard deviations from calculations which assume symmetric and normal data distribution about an average (Quinn and Quinn, 2010). The 95% confidence limits for the groups were calculated and differences were considered significant when no overlap occurred. Multiple comparisons were made using Tukey HSD at 95% confidence levels between all data sets in order to test the hypotheses outlined.

4.2.4 Scanning Electron Microscopy (SEM)

The number of fractured fragments from each EBFS test were counted and examined visually. SEM was performed on a representative sample from the unrepaired 3 mm access cavity group (Group B). An unused and used diamond rotary bur were examined using SEM to determine the damage and bur condition after use. Specimens were air dried and gold sputter-coated (Cressington Sputter Coater, 108 auto) to permit conduction at a thickness of 14 nm and then examined using a SEM (Zeiss Supra™ 65VP).

4.3 Results

The assumption of homogeneity of variance (Levene's test) was satisfied (F= 1.72, DF= 5, p-value= 0.13), however, the assumption of normality (Shapiro-Wilkes test) was violated (W = 0.92, p-value = <0.01). Two outliers were identified as the source of violation (in Group C and E). These two datapoints were substantially higher than the other readings in their corresponding groups. Justification to remove these observations from the dataset was made in that the values corresponded with specimens where the thickness to diameter ratio was decreased to below that of the average and also the internal representative access cavity diameter was larger than the average. Thus, the volume of material under stress was less than average. The 3 mm access cavity with a low modulus of elasticity resin composite repair (from Group C) had an EBFS value of 166.33 MPa, the specimen thickness was 1.38 mm compared with a Group mean of 1.46 (0.11) mm, the internal cavity was 3.09 mm compared with a Group mean of 3.03 (0.04) mm. The 5 mm access cavity with no repair (from Group E) had an EBFS value of 153.9 MPa, the specimen thickness was 1.22 mm compared with a Group mean of 1.53 (0.09) mm, the internal cavity was 5.49 mm compared with a Group mean of 5.06 (0.11) mm. When the two data points were removed the assumption of homogeneity of variance (Levene's test) was still satisfied (F= 1.52, DF= 5, p-value= 0.19), and the assumption of normality (Shapiro-Wilkes test) was also satisfied (W = 0.99, p-value =0.61). The balanced nature of the design was however disrupted due to the removal of two outlying data points from 2 Groups (Group C and E) and also due to one pre-test failure (Group G).

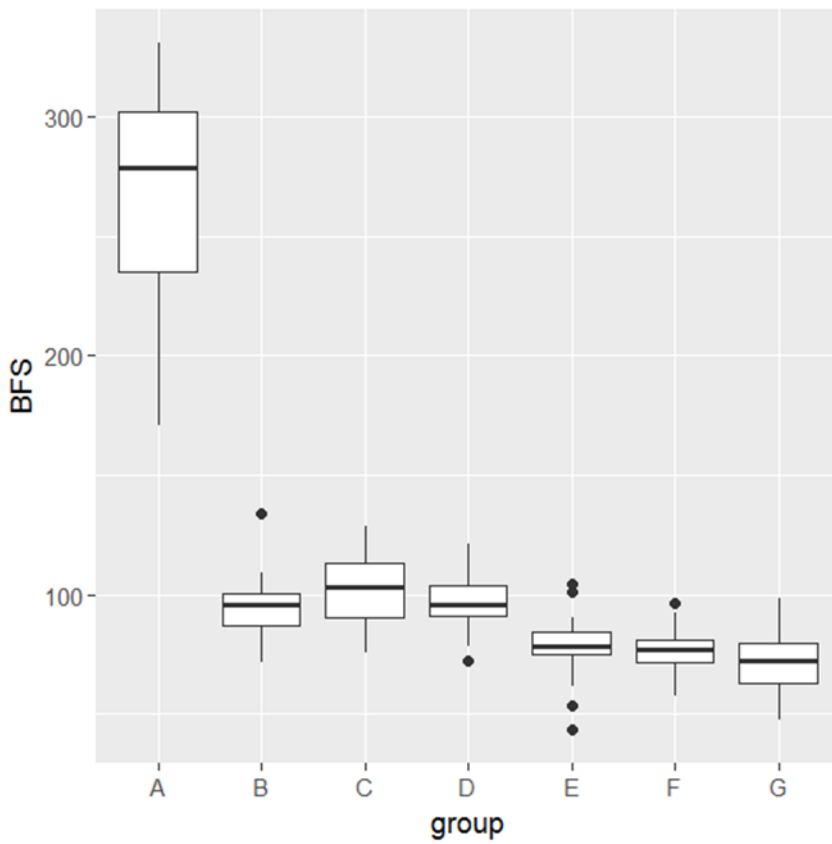


Figure 4.2. Boxplot results for the equibiaxial flexural strength (MPa) based on access cavity dimension and modulus of elasticity of the repair material. Groups A= intact disc, B= 3 mm access cavity with no repair, C= 3 mm access cavity with LMOE RC repair, D= 3 mm access cavity with HMOE RC repair, E= 5 mm access cavity with no repair, F= 5 mm access cavity with LMOE RC repair, G= 5 mm access cavity with HMOE RC repair.

Mean EBFS values are presented in Table 4.2 and displayed in a boxplot in Figure 4.2. Mean EBFS for the intact group (A) was significantly different ($p < 0.05$) from all other groups. The mean flexure strength was 267.5 (43.7) MPa for the intact specimens (Group A), this value decreased to

94.7 (12.1) MPa when a 3 mm cavity (Group B) was prepared and further decreased to 78.2 (12.6) MPa when a 5 mm cavity (Group E) was prepared in LDGC disc substrates. Results from the Tukey post hoc tests (Table 4.4) reveal a statistical difference ($p<0.001$) in EBFS between Group B and Group E. All Groups (B, C and D) with 3 mm access cavities were significantly ($p<0.001$) different from all groups (E, F and G) with 5 mm access cavities. There was no significant difference in EBFS values between multiple comparisons within the 3 mm (Groups B, C, D) access cavity groups or the 5 mm groups (E, F, G). A cavity-repair interaction effect was also observed (Table 4.3).

GROUP	MEAN BFS ± STANDARD DEVIATION (MPA)	OBSERVATIONS (N)
A	267.5 ± 43.7	30
B	94.7 ± 12.1	30
C	102.6 ± 13.9	29
D	96.6 ± 11.1	30
E	78.2 ± 12.6	29
F	76.1 ± 8.9	30
G	71.7 ± 12.4	29

Table 4.2. Descriptive statistics of equibiaxial flexural strength (MPa) including standard deviations for the dataset. Groups A= intact disc, B= 3 mm access cavity with no repair, C= 3 mm access cavity with LMOE RC repair, D= 3 mm access cavity with HMOE RC repair, E= 5 mm access cavity with no repair, F= 5 mm access cavity with LMOE RC repair, G= 5 mm access cavity with HMOE RC repair.

	Df	Sum sq	Mean sq	F value	p-value
Cavity	1	22540.0	22540.0	158.59	< 2e-16
Repair material	2	777.2	388.6	2.73	0.07
Cavity: repair material	2	839.4	419.7	2.95	0.05
Residuals	171	24304.1	142.1		

Table 4.3. A 2-way analysis of variance table for groups B-G, response variable is EBFS. Groups A= intact disc, B= 3 mm access cavity with no repair, C= 3 mm access cavity with LMOE RC repair, D= 3 mm access cavity with HMOE RC repair, E= 5 mm access cavity with no repair, F= 5 mm access cavity with LMOE RC repair, G= 5 mm access cavity with HMOE RC repair.

Group comparisons	Mean Difference	95% Confidence Interval	p adjustment	Statistical significance
E-B	-16.55	(-25.50, -7.60)	<0.001	*
C-B	7.86	(-1.09, 6.81)	0.121	
F-B	-18.66	(-27.53, -9.78)	<0.001	*
D-B	1.84	(-7.03, 10.72)	0.991	
G-B	-22.98	(-31.93, -14.03)	<0.001	*
C-E	24.41	(15.39, 33.43)	<0.001	*
F-E	-2.11	(-11.06, 6.84)	0.984	
D-E	18.39	(9.44, 27.34)	<0.001	*
G-E	-6.43	(-15.46, 2.59)	0.316	
F-C	-26.52	(-35.47, -17.57)	<0.001	*
D-C	-6.02	(-14.97, 2.93)	0.383	
G-C	-30.84	(-39.87, -21.81)	<0.001	*
D-F	20.50	(11.63, 29.37)	<0.001	*
G-F	-4.32	(-13.27, 4.63)	0.732	
G-D	-24.82	(-33.77, -15.88)	<0.001	*

Table 4.4. Tukey HSD post hoc analysis of groups B-G. Groups A= intact disc, B= 3 mm access cavity with no repair, C= 3 mm access cavity with LMOE RC repair, D= 3 mm access cavity with HMOE RC repair, E= 5 mm access cavity with no repair, F= 5 mm access cavity with LMOE RC repair, G= 5 mm access cavity with HMOE RC repair. * denotes statistical difference between groups.

4.3.1 Weibull Analysis

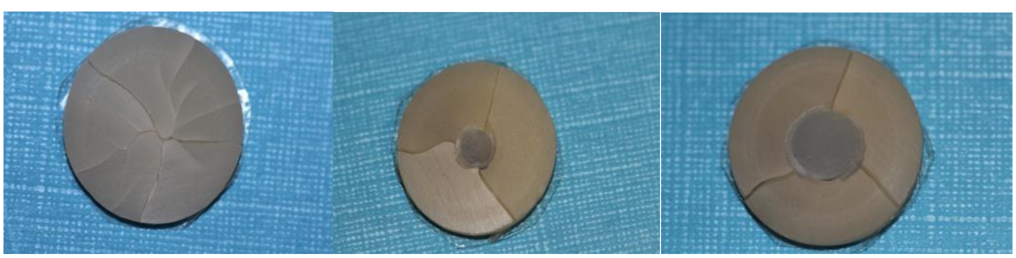
The Weibull moduli are given for each Group in Table 4.5. A significant difference existed when confidence intervals did not overlap. The Weibull moduli (*m*) increased for both the 3 mm and 5 mm access cavity geometries when they were repaired with either composite resin, however the differences were not significant.

Material	Hole size (mm)	Weibull modulus (shape parameter)	95% CI	Characteristic strength (Weibull scale parameter)	95% CI
A	0.0	7.69	(5.43, 9.94)	285.29	(278.17, 292.42)
B	3.0	7.32	(5.57, 9.07)	100.11	(94.91, 105.30)
C	3.0	8.59	(6.15, 11.02)	108.54	(103.68, 113.40)
D	3.0	9.30	(6.87,11.74)	101.47	(97.33, 105.60)
E	5.0	7.21	(5.25, 9.18)	83.25	(78.82, 87.67)
F	5.0	9.31	(6.86,11.76)	79.95	(76.70, 83.20)
G	5.0	6.51	(4.71, 8.32)	76.89	(72.34, 81.43)

Table 4.5. Weibull shape (modulus) and scale (characteristic strength) parameters including 95% confidence intervals for the dataset. Groups A= intact disc, B= 3 mm access cavity with no repair, C= 3 mm access cavity with LMOE RC repair, D= 3 mm access cavity with HMOE RC repair, E= 5 mm access cavity with no repair, F= 5 mm access cavity with LMOE RC repair, G= 5 mm access cavity with HMOE RC repair.

4.3.2 Fracture patterns

The intact specimens exhibited a classic fracture pattern where several radial cracks emanated from the centre of the specimen (Figure 4.2), which is indicative of the failure pattern for high-strength ceramic materials (ASTM C1499-05, 2005). A total of 68% (from a 60% - 87% range) of fractures from the groups B-G consisted of fracture in three equidistant fragments. A total of 9% of fractures consisted of two fragments in a 2:1 ratio and 22% involved four fragments in various different fragment ratios. The failure patterns for groups B-G were indicative of ceramic materials classified with low EBFS. No difference between the fracture patterns were observed between the two access cavity dimensions (Figure 4.3).



a) b) c)

Figure 4.3. Photograph of lithium disilicate glass-ceramic disc substrates exhibiting a) a classic high-strength fracture pattern for an intact specimen b) a low-strength fracture pattern for a 3 mm representative endodontic access cavity repaired with a high modulus of elasticity resin composite, c) a low-strength fracture pattern for a 5 mm representative endodontic access cavity repaired with a high modulus of elasticity resin composite.

A higher percentage fracture of the resin composite repair, 47% and 57%, was observed for specimens with the low modulus of elasticity repair material for 5 mm and 3 mm access cavities, respectively. Conversely, for the higher modulus of elasticity resin composite repair, 17% and 13% of fractures involved the repair material for 5 mm and 3 mm, respectively.

The coefficient of variance for the diameter of the representative endodontic access cavity for each group was well tolerated (range 1.3% - 2.8%) and reflected a high degree of accuracy.

4.3.3 Scanning Electron Microscopy (SEM)

SEM images clearly show the sharp abrasive diamond particles embedded in the bur prior to use (Figure 4.4). Depreciation of the diamond grit particles are evident after use, the angular shape of the diamond particles become worn and clogged with debris after use (Figure 4.5). A representative specimen from the unrepaired 3 mm access cavity group (Group B) exhibited a clean fractured surface with a chip on the bur exit side at the access cavity (Figure 4.6).

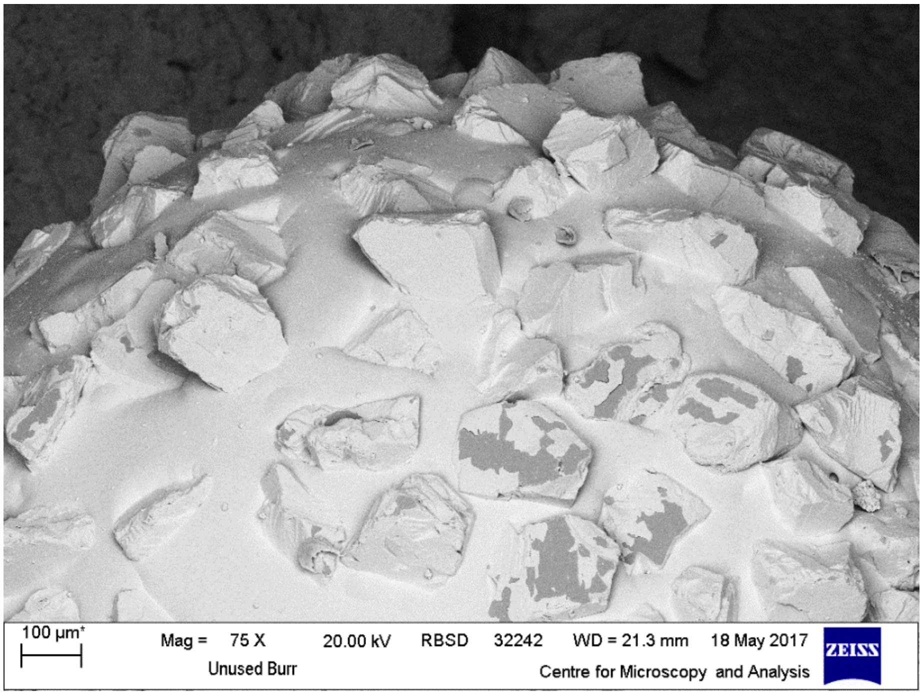


Figure 4.4. SEM (× 75) image of a new diamond abrasive bur demonstrating clean, sharp diamond grit particles.

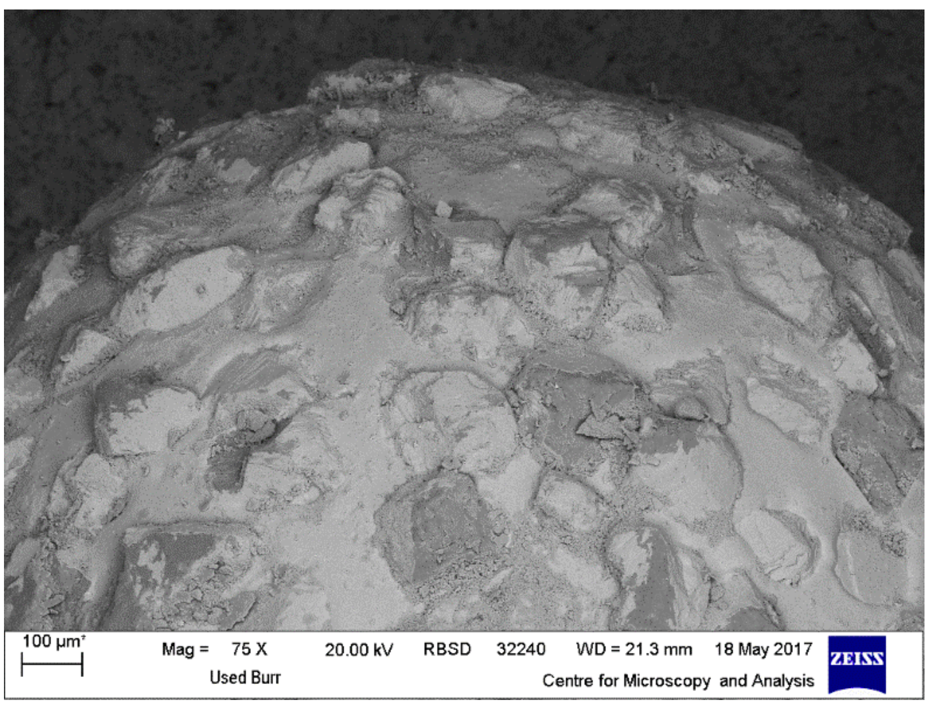


Figure 4.5. SEM (× 75) image of a used diamond abrasive bur demonstrating worn diamond grit projections which are also clogged with ceramic particles.

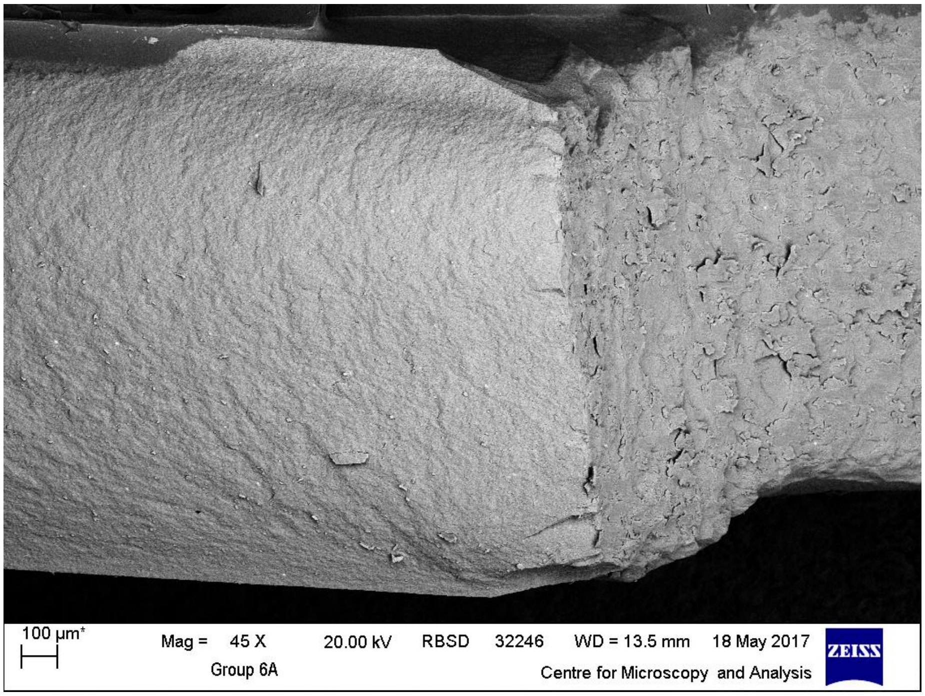


Figure 4.6. SEM (× 45) of the fractured surface of a LDGC disc, note the smeared surface (right) where the representative endodontic access cavity (unrepaired) has been prepared in contrast to the clean fracture surface (left). Note the chip at the bur exit point between adjacent surfaces (bottom).

4.4 Discussion

The use of simplified disc geometries enabled experimental standardisation for, reliable data collection, to compare and potentially extrapolate findings to the clinical scenario. The concentric 'ring-on-ring' loading configuration of the testing apparatus in the current study 'uniquely' facilitated the *in vitro* EBFS determination for LDGC disc substrates with representative endodontic access cavities which would otherwise have been impossible using alternative methods for testing flexure strength.

The null hypothesis for a) is rejected, b) is not rejected. It is evident that the EBFS of intact LDGC disc specimens was significantly ($p<0.5$) reduced when a representative endodontic access cavity was prepared in the specimens. This is a similar effect to findings in the existing literature for other glass-ceramic materials (Kelly *et al*., 2014 and Kelly *et al*., 2017). The EBFS was significantly ($p<0.001$) reduced when the dimension of the access cavity was increased from 3 mm to 5 mm. Completion of a resin composite repair of the access cavity did not increase the EBFS in either 3 mm or 5 mm access cavity disc specimens. In addition, it was also found that using a resin composite with an increased modulus of elasticity to complete the repair did not result in an increase in EBFS in either 3 mm or 5mm access cavity disc specimens.

Removal of the two data points which caused violation of the assumptions of normality permitted the data to be analysed by parametric analysis. This is generally more desirable since *post hoc* tests will permit identification of significant differences more clearly. Justification for removal of the outlying data points was made on the basis that the specimen thickness to diameter ratio was reduced below the group average, the internal access cavity dimension was increased beyond the corresponding mean values. Effectively, this resulted in a decreased volume of material being tested and higher EBFS values were reported for both specimens. This could possibly be attributed to the phenomena of strength-scaling (Morrell, 2007, Quinn and Quinn, 2010), whereby the reduced volume of material placed under stress has a statistically decreased probability of containing a strength reducing flaw in the bulk material. The Weibull moduli of the intact material was reduced slightly when a 3 mm access cavity was prepared in it, it was further reduced when a 5 mm access cavity was prepared, however, the effect was not significant. This is at odds with findings in the literature, where a significant decrease in Weibull modulus was reported when an endodontic access cavity was prepared in leucite and feldspathic disc materials (Kelly *et al*., 2014, Kelly *et al*., 2017).

The literature has not adequately addressed the impact of endodontic access cavity preparation in all-ceramic crowns on the mechanical properties (Gorman *et al*., 2016). There is strong evidence that microcracks (sharp) localised to the access cavity occur (Teplisky and Sutherland, 1985, Sutherland *et al*., 1989, Cohen and Wallace, 1991, Haselton *et al*., 2000, Wood *et al*., 2006, Beck *et al*., 2010, Bompolaki *et al*., 2015), these are potentially a more detrimental flaw type than pores (blunt) from which catastrophic fracture may occur (Quinn and Quinn, 2010). The flaw sensitivity of ceramic materials is an inherent limiting factor to their use and is further compounded by moisture in load bearing dental situations which render the material susceptible to unstable crack propagation without prior visible deformation (Ritter, 1995, Jung *et al*., 2000). Cementation with resin composite has been shown to favourably alter flaw morphology, conferring a positive influence on the flexure strength of glass-ceramics (Pagniano *et al*., 2005). The mechanical properties are reported to have been maintained in glass-ceramic restorative materials luted with resin composite where endodontic access cavity preparation had evidently caused strength reduction (Qeblawi *et al*., 2011 and Kelly *et al*., 2017).

LDGC is a challenging material to machine compared with other glass-ceramics, as a result this may give rise to increased heat generation which the coolant from the dental handpiece has limited ability to dissipate (Song *et al*., 2016). This has the potential to initiate a higher number of heat-induced microcracks from which failure may occur, this may also be a contributing factor to the very significant (approximately 60 - 70%) reduction in strength observed in the current study which results from endodontic access cavity preparation in LDGC substrates. The damage to the diamond abrasive particles in the bur is evident after use, used diamond burs may require greater force to remove material and therefore increase the amount of heat-induced microcracks in the material.

The characteristic strength calculated for the intact LDGC discs in the current study 267.5 ± 43.7 MPa is at the lower end of what is reported in the literature (213.8 - 440 MPa) (Pagniano *et al*., 2005, Albakry *et al*., 2003). Potential explanations for this, include the surface finish attained for the disc specimens (180 grit SiC paper) and the ageing regime which the material was subjected to. Polishing regimes necessary to achieve a mirror surface induce compressive stresses in the surface of the material which lead to the inflation of strength values reported (Giordano *et al*., 1995, Pagniano *et al*., 2005). Thermocycling protocols employed *in vitro* to mimic the temperature fluctuations of the oral environment contribute to ageing and result in, reduced mechanical properties and, arguably more clinically realistic results (Kelly, 1999, Jung *et al*., 2000, Kelly *et al*., 2010, Rekow *et al*., 2011). Thermocycling can be particularly detrimental to the bond created between a resin composite and ceramic material but this is relatively controversial (Gresnigt *et al*., 2016).

The hypothesis that a repair material with a stiffer modulus of elasticity would increase the overall strength was rejected. While the evidence is not strong in the current study it does however, associate the lower MOE repair material with higher EBFS for the smaller (3 mm) access cavity. A resin composite material with a low modulus of elasticity may achieve better wettability with the ceramic due to its lower viscosity, thus making more intimate contact and penetrating further into surface cracks compared with a packable resin composite. The flowable resin composite may seal the crack face which may exert compressive forces at the crack tip as a result of polymerisation shrinkage which effectively reduces crack length (Pagniano *et al*., 2005). The inherent greater weakness of the LMOE resulted in a higher percentage (47% and 57%) of specimen fractures which involved the resin composite repair material compared with the HMOE resin composite (17% and 13%), respectively. An alternative hypothesis is that, the fracture may have been forced through the LMOE resin composite due to increased bonding brought about by intimate adaptation with the ceramic due to its greater fluidity. In addition, the bond between the ceramic and resin composite with a lower modulus may be less adversely affected by thermocycling due to its greater degree of flexibility. An added biological advantage to this would be the potential to reduce coronal microleakage and bacterial ingress.

The current study has shown that the initial high base-line strength of LDGC's cannot be maintained when an endodontic access cavity is prepared in it. While it was not statistically significant, a smaller (3 mm) endodontic access cavity repaired with a lower modulus of elasticity resin offered the best results in terms of BFS compared with the alternative interventions. While the strength of LDGC material was significantly reduced with the introduction of an endodontic access cavity, the characteristic flexure strength is comparable to those of some intact commercially available glass-ceramics such as feldspathic (52.2 ± 7.8 MPa) (Kelly *et al*., 2014) and leucite (117.2 ± 16.6 MPa) (Kelly *et al*., 2017) glass-ceramics. This, coupled with the potentially beneficial effects of adhesive cementation on glass-ceramic reinforcement described in other studies for, crowns (Qeblawi *et al*., 2011) and discs (Kelly *et al*., 2017), suggest that replacement restorations may be unnecessary for endodontically accessed LDGC crowns and that repaired restorations may be retained as a definitive restoration particularly in non-load bearing areas.

4.5 Conclusion

The preparation of an access cavity in representative lithium disilicate glass-ceramic discs resulted in a significant reduction in strength. Increasing the dimension of the access cavity further decreased the EBFS. Repair with resin composite did not increase the EBFS, increasing the MOE of the resin composite did not increase the EBFS.

The strength of lithium disilicate glass-ceramic materials which have undergone an endodontic access cavity preparation with a resin composite repair are comparable to lower strength intact glass-ceramic restorative materials in this category and may therefore continue as viable long-term restorations, particularly in non-load-bearing areas where restorations have been adhesively cemented.

Chapter 5

Effect of endodontic access cavity size and repair material on the failure load of Lithium Disilicate glass-ceramic crowns: an *in vitro* study

This chapter is under peer review as;

Effect of endodontic access cavity size and repair material on the failure load of Lithium Disilicate glass-ceramic crowns: an *in vitro* study

Catherine M. Gorman, Noel J. Ray, Erica Donnelly-Swift and Francis M. Burke

Abstract

Objectives: The purpose of this study was to evaluate the effect of cavity dimension and repair with a resin composite material on the failure load of endodontically treated lithium disilicate crowns *in vitro*. The null hypotheses were that failure load is affected by a) the preparation of an access cavity, b) the geometry of the access cavity, c) completion of a restorative repair, within the parameters used.

Methods: 75 lithium disilicate crowns were randomly allocated to five groups. Group A (control), Groups B and D (rhomboidal access cavity) and Groups C and E (rectangular access cavity). The access cavities were either repaired with resin composite (D, E) or not (B, C). The crowns were stored for a total of three weeks at 37 ± 2ºC in water. They were loaded with a 15 mm spherical chromium steel ball in compression at a rate of 1mm/min until failure in a universal testing machine and the failure load was recorded. Statistical analysis included ANOVA followed by Tukey HSD post hoc tests to determine if there is a difference among group means. Weibull analysis was also performed for each group.

Results: Mean failure loads for Groups A, B, C, D and E were 1506.2 ± 171.7 N, 1352.2 ± 201.2 N, 722.3 ± 133.2 N, 1710.8 ± 159.2 and 1598.7 ± 223.4, respectively. The intact Group A was significantly different from Group C ($p<0.001$), but not B ($p=0.15$). There was no significant difference ($p<0.05$) between the intact crown group and both Groups D and E which had been repaired with a resin composite.

Conclusions: The failure load of lithium disilicate crowns was not affected with the preparation of a rhomboidal endodontic access cavity but was significantly different with the preparation of a rectangular access cavity. The failure load was restored to at least its original value when a resin composite restoration was completed.

Clinical significance: Overzealous preparation of an endodontic access cavity has a deleterious effect on the failure load of lithium disilicate glass-ceramic crowns. However, the original value may be regained at least in the short-term when repair of the access cavity with resin composite is made. If the access cavity to crown ratio is excessive, a replacement crown may be required long-term.

5.1 Introduction

The placement of dental crowns has increased exponentially in recent years (Kelleher, 2012 and Christensen, 2013). However, each stage in the process of dental crown fabrication has been identified with potential to harm the dentine-pulp complex (Dahl, 1977), which may result in subsequent need for endodontic treatment. The incidence of endodontic treatment after crown placement is significant in general dental practice (Goldman *et al*., 1992, Christensen, 1994, Trautmann *et al*., 2000b). From a pool of 543 experienced dentists (202 endodontists, 175 prosthodontists and 166 general practitioners), 36% estimated that crowned teeth would require endodontic treatment within a 0-5 year period and 52% within a 5-10 year period (Trautmann *et al*., 2000a). Indeed, in anticipation of the eventual need for root canal access and to circum'vent' the preparation of an access cavity *in situ*, Burrell and Goldberg (1974) proposed, a 'vented' crown design (inclusion of an occlusal escape channel) when a poor prognosis for pulp vitality was expected.

There has been a fundamental shift in the materials used for dental crown restorations from, metal-ceramic to metal-free restorations (Christensen, 2011, Christensen, 2014). All-ceramic crowns are most desirable in terms of aesthetics compared with their metal-ceramic equivalents (Brunton *et al*., 1999, Christensen, 2011, Zhang *et al*., 2013). New generations of high toughness ceramic materials have facilitated the extended use of all-ceramics to posterior restorations (Brunton *et al*., 1999, Christensen, 2011, Zhang *et al*., 2013).

Preparing an endodontic access cavity in an all-ceramic crown *in situ* is a task complicated by the high fracture toughness and resistance of ceramic materials to machining (Song *et al*., 2016). Machining ceramic materials result in surface flaws and subsurface damage, such damage is associated with limiting the in-service lifespan of dental restorations (Song *et al*., 2009, Coldea *et al*., 2015). Several studies have reported machining damage which result in microcracking (Teplisky and Sutherland, 1985, Sutherland *et al*., 1989, Cohen and Wallace, 1991, Haselton *et al*., 2000, Wood *et al*., 2006, Beck *et al*., 2010, Kelly *et al*., 2014, Bompolaki *et al*., 2015, Kelly *et al*., 2017). Stress concentration is perpetuated by flaws and exacerbated by moisture, the combination of which, increase the likelihood of catastrophic failure when a component is placed under load (Ritter, 1995, Jung *et al*., 2000). As shown from other research (Sabourin *et al*., 2005, Beck *et al*., 2010) the light source used to detect damage-induced cracks can influence the results obtained. Diamond burs are the most effective choice for preparing access cavities in all-ceramic crowns (Gorman *et al*., 2016). The repair of an access cavity is routinely completed (Trautmann *et al*., 2000b) and is desirable to, ensure a coronal seal, reduce microleakage and maintain the occlusal anatomy for function.

A limited number of *in vitro* studies have investigated the impact of endodontic access cavities on the failure loads of all-ceramic crown restorations (Gorman *et al*., 2016), crown types include, sintered alumina core with a glass-ceramic veneer (Stokes *et al*., 1988), milled alumina and zirconia core with a glass-ceramic veneer (Wood *et al*., 2006) and monolithic lithium disilicate glass-ceramic (Qeblawi *et al*., 2011, Bompolaki *et al*., 2015) materials. Significant ($p<0.05$) reduction in failure load of lithium disilicate glass-ceramic (LDGC) crowns was observed when an endodontic access cavity was prepared with an ultra-coarse (150-180 µm) compared with a standard (126 µm) diamond rotary instrument (Qeblawi *et al*., 2011). The same study reported that the luting cement also contributed a significant effect on the failure load, with resin composite (RC) yielding higher failure load results ($p<0.05$) compared with zinc phosphate cement. None of the studies (Stokes *et al*., 1988, Wood *et al*., 2006, Qeblawi *et al*., 2011 Bompolaki *et al*., 2015) determined the failure load of the crown with an unrestored access cavity and therefore the effect of the RC repair, as an intervention on failure load cannot be conclusively ascertained. Two recent studies (Hussein *et al*., 2016, Mokhtarpour *et al*., 2016), explored the effect of screw access channels on the failure load of all-ceramic implant crowns. The presence of a screw-access channel had no significant ($p>0.05$) impact on the failure load of selected ceramic materials (monolithic zirconia, veneered zirconia, lithium disilicate) compared with crowns without an access channel (Hussein *et al*., 2016). However, the failure load sustained by the different materials showed significant differences ($p<0.05$) from each other. In this study the crowns were milled with an access channel, therefore any damage induced from machining could have been alleviated as a result of the sintering or crystallisation process. The effect of preparing a screw access channel in implant-supported zirconia crowns was not significant ($p=0.44$) when the access channels were manually prepared before or after sintering (Mokhtarpour *et al*., 2016). However, both before ($p<0.001$) and after ($p<0.0001$) groups were significantly different from the intact equivalent.

LDGC is amongst the most popular contemporary all-ceramic dental restorative materials available (Della Bona and Kelly, 2008). Lithium disilicate crystals have an interlocking microstructure which is an effective mechanism to deflect propagating cracks in the glass-ceramic matrix (Aboushelib and Elsafi, 2016). It is a particularly attractive restorative material due to its excellent mechanical properties combined with a range of options for translucency levels, with the added potential for surfaces to be reliably primed for bonding to tooth structure. Endodontic access cavities in LDGC crowns can be adhesively repaired with RC (Qeblawi *et al*., 2011, Bompolaki *et al*., 2015). The resistance of polycrystalline ceramics such as zirconia to acid make adhesion with RC unsuccessful (Tzanakakis *et al*., 2016). Phosphate acid ester monomers (methacryloyloxy-decyl-dihydrogen-phosphate) have demonstrated an ability to mediate the adhesion between RC and zirconia (Tzanakakis *et al*., 2016), however the success of this bond is diminished with ageing (De Souza *et al*., 2014). It is questionable therefore how a RC repair of an endodontic access cavity can confer any strengthening effect on the failure load of alumina and zirconia crowns, which was the conclusion in one study (Wood *et al*., 2006).

A higher access cavity to crown ratio (Sutherland *et al*., 1989) was associated with increased risk of catastrophic crown failure during cavity preparation (Sutherland *et al*., 1989, Cohen and Wallace, 1991, Haselton *et al*., 2000). The presence of additional canals, or the need to facilitate instrumentation access and speed of treatment may result in larger than ideal access cavity openings leading to increased access cavity to crown ratio (Johnson and Williamson, 2015). Additionally, root canals which are incongruously located due to morphological differences between the original and restored crown can lead to an overzealous access opening. Posterior teeth have a higher percentage of root and canal aberrations compared with anterior teeth (Gutmann and Fan, 2015). The mandibular first molar has normal recurring features with a number of atypia's (Maggiore *et al*., 1998). The usual configuration for the mandibular first molar is two canals in the mesial root, although three are possible (Vertucci, 1984) and one canal in the distal root, this will result in an approximately triangular or rhomboidal endodontic outline access form (Figure 5.1a)). In circa one third of cases, a second canal is present in the distal root (Skidmore and Bjorndal, 1971, Hartwell and Bellizzi, 1982) necessitating a rectangular outline access opening form (Figure 5.1b)). Considerable variation in root canal morphology is found amongst various ethnic population groups (Gutmann and Fan, 2015). Variation in root canal morphology also changes with the progression of age (Peiris *et al*., 2008). A larger access cavity outline form may also be recommended for a geriatric or medically compromised patient to facilitate ease of access and speed of treatment. The mandibular first molar was selected in the current study since it is the tooth that most frequently requires endodontic treatment (Yousuf *et al*., 2015), early eruption combined with favourable occlusal features may favour this. Maximum occlusal forces occur between the maxillary and mandibular first molar dentition (Tortopidis *et al*., 1998).

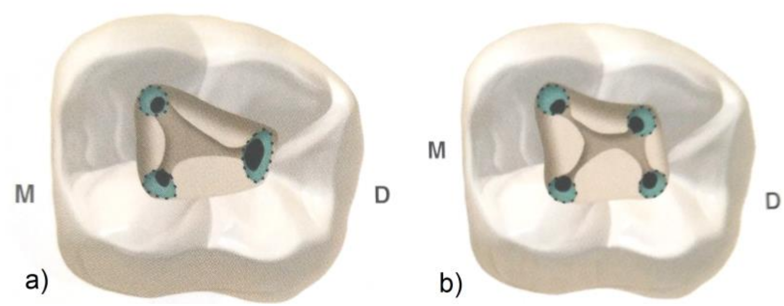


Figure 5.1 Diagram of outline endodontic access openings based on the presence of a) 3- canals and b) 4- canals for a mandibular first molar tooth (Wilcox, 2015).

The aim of the current investigation was to identify how the load to failure of LDGC mandibular first molar crowns are affected by endodontic access cavity dimension and repair with RC. Within the limitations of the experimental protocol, the null hypotheses was that failure load was not affected by;

a) The preparation of an access cavity,

b) The dimension of access cavity,

c) Repair of the access cavity with a RC material.

5.2 Materials and Methods

5.2.1 Fabrication of LDGC crown specimens

A plastic tooth (DPS Model tooth No 36, Kavo, Germany) was reduced uniformly by 1.5 mm with a chamfer margin of 1.0 mm in width to receive a monolithic IPS e.max® Press restoration. Impressions of the preparation were made using a high accuracy silicone duplicating material (Exactosil, Bredent, Germany).

Epoxy resin (10 mls: RX900D/NC, Robnor resins, Wiltshire, UK) and epoxy hardener (3.8 mls) were combined together with a small spatula until completely mixed, silicone moulds were then carefully filled with the epoxy resin under vibration using a small metal instrument. The dies were allowed to set in air for 72 hours, then removed from the moulds and stored in a polythene bag until required, any imperfect dies were discarded.

The tooth preparation and the full contour tooth were both scanned using a contact scanner (Incise scanner, Renishaw, UK) the images were superimposed on each other to produce an image of ‘the crown’. 75 crowns were milled from wax billets (Renishaw, UK) and invested in a phosphate bonded investment material (IPS PressVest Speed, Ivoclar Vivadent AG, Schaan/Liechtenstein) and the manufacturer’s instructions were followed for the burnout, pressing and divesting of the IPS e.max® Press material (IPS e.max® Press Instructions for use, Ivoclar Vivadent AG, Schaan/ Liechtenstein).

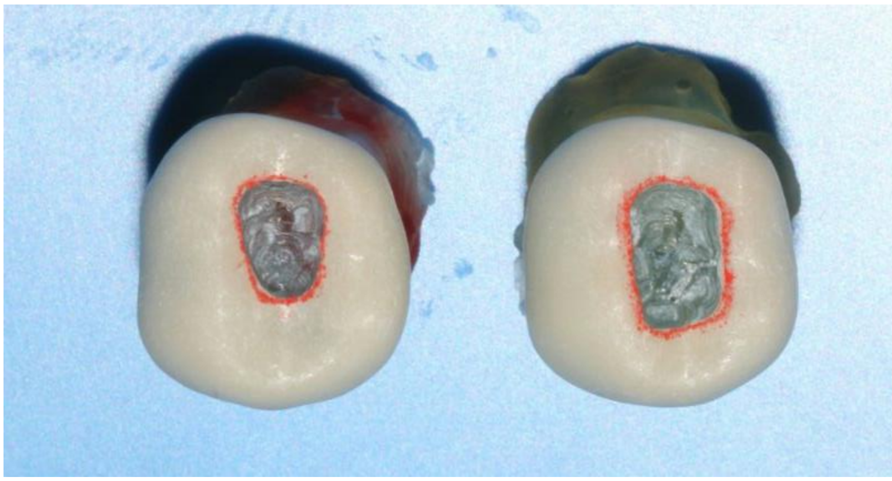
The crowns were immersed in acid (IPS e.max® Press Invex liquid, Ivoclar Vivadent AG, Schaan/Liechtenstein) for 15 minutes to remove the reaction layer. The crowns were then rinsed in running water, dried thoroughly and the intaglio surface was airborne-particle abraded with 110 µm alumina particles at 1 bar pressure at a distance of 10 mm. The area where the sprue was attached was reshaped using a ceramic grinding bur (P.ZR21.040.HP-1, Frank Dental GmbH, Germany). Any imperfections on the fitting surface were removed with a small diamond bur (D.805.014.HP, Frank Dental GmbH, Germany), the crown was then checked for accuracy of fit on a Type IV stone die replica. The crowns were subjected to a simulated glaze firing cycle at 770ºC and held for 1 minute under vacuum, then removed from the furnace (P310, Ivoclar Vivadent AG, Schaan/Liechtenstein) and allowed to cool to room temperature.

5.2.2 Resin composite cementation of LDGC crown specimens

A simple white light emitting diode (LED) light was passed through the crowns to ensure specimens were devoid of visible cracks or flaws. The internal surface of each crown was etched for 20 seconds with 5% hydrofluoric (HF) acid (IPS Ceramic Etching gel, Ivoclar Vivadent AG, Schaan/Liechtenstein). The restoration was thoroughly rinsed with water and dried with oil-free air. A silane primer/bonding agent (Monobond-Plus, Ivoclar Vivadent AG, Schaan/Liechtenstein) was applied to the etched surface with a microbrush (Applicator tips, Dentsply, UK) and allowed to react for 60 seconds, after which, the excess was dispersed with a stream of oil-free air. The luting composite (Multilink Automix, Ivoclar Vivadent AG, Schaan/Liechtenstein) was applied to the internal surface of the crown, then each crown was seated slowly on the die while the excess was displaced. The crown was 'tacked' in position by light curing (5W LED, 440-480 nm wavelength range, Lumion, Planmeca, Finland) in quarter segments at the margins for a total of 10 seconds while being held firmly in place with finger pressure on the occlusal surface. The excess was removed from the margins with a small metal instrument. A 200g mass was gently placed on the occlusal surface to maintain a uniform constant pressure, then the crown was fully light cured (5W LED, 440-480 nm wavelength range, Lumion, Planmeca, Finland) for 20 seconds at each quarter segment at a distance of <10 mm. The crowns were stored for 3 weeks at 37 ± 2ºC in ultra-pure water.

5.2.3 Preparation of endodontic access cavities in LDGC crown specimens

The access cavity geometry was based on classic textbook guidelines (Johnson and Williamson, 2015) for either a three canal rhomboidal shaped (Groups B and D) or a four canal rectangular shaped (Groups C and E) access cavity (Figure 5.2). After 1 week, 60 crowns from were randomly removed from water storage and 30 crowns were randomly assigned to receive a rhomboidal access cavity and 30 a rectangular access cavity. The 15 crowns which remained in storage were labelled Group A. The position and size of the access cavity was standardized by marking the outline on the occlusal surface with a wax pen (Margin liner, Kerr Dental, USA) for each crown and compared with the diagram. A new coarse-grit (107-180 µm) round diamond rotary cutting bur (D.801.023.G.FG Frank Dental GmbH, Germany) was used to perforate each specimen in a high-speed handpiece (Planmeca, Finland) under a continuous water spray by a single operator. The access cavity was extended to the outline of the marker using a fine-grit (27-76 µm) round end cylinder (D.881.016.G.FG Frank Dental GmbH, Germany), the walls of the cavity were kept as close to parallel as visually possible. The crown was thoroughly rinsed with water spray and dried with oil free air. The crowns with a rhomboidal access cavity were randomly divided between Groups B and D, similarly the crowns with a rectangular access cavity were randomly between Groups C and E. Groups B and C (unrepaired) were returned to storage in ultra-pure water at 37ºC for a further 2 weeks.



a) b)

Figure 5.2 LDGC mandibular first molar crown with, a) rhomboidal access cavity, b) rectangular endodontic access cavity (access opening design as described in Carrotte, 2011).

5.2.4 Resin composite repair of access cavities in LDGC crown specimens

Groups D and E were repaired immediately with a RC material (Table 5.1). The margins of the access cavity were etched for 20 seconds with 5% aqueous HF acid (IPS Ceramic Etching gel, Ivoclar Vivadent AG, Schaan/Liechtenstein) and then thoroughly rinsed with water spray and dried with oil free air. A silane primer/bonding agent (Monobond-Plus, Ivoclar Vivadent AG, Schaan/Liechtenstein) was applied to the access cavity margins for 60 seconds with a microbrush (Applicator tips, Dentsply, UK) and then dried with a stream of oil-free air. A thin layer of flowable RC

(Tetric EvoFlow, Ivoclar Vivadent AG, Schaan/Liechtenstein) was placed on the cavity margins and gently thinned with oil-free air, then light cured for 20 seconds. A packable RC (Tetric EvoCeram, Ivoclar Vivadent AG, Schaan/Liechtenstein) was adapted into the mesial half of the access cavity and light cured for 20 seconds, the distal half was completed to restore the shape in the same manner and light cured for 20 seconds, an additional 20 second cure was given overall. The specimens were returned to storage for a further 2 weeks.

Group	Description	Access cavity repair
A	Intact crown	N/A
B	Small rhomboidal access cavity	Unrepaired
C	Large rectangular access cavity	Unrepaired
D	Small rhomboidal access cavity	Repaired with RC*
E	Large rectangular access cavity	Repaired with RC*

*Tetric EvoCeram, Ivoclar Vivadent AG, Schaan/Liechtenstein

Table 5.1 Descriptive summary of experimental Groups A-E.

5.2.5 Orientation of the LDGC crown specimens

The master model was placed horizontally in a dental surveyor (Ney surveyor, Dentsply, UK), and guided 15 degrees from the perpendicular with a simple protractor. This ensured that the load was transmitted onto the mandibular first molar analogous to the angulation of loading as found between the maxillary and mandibular first molar teeth in a normal arrangement of the dentition (Dempster *et al*., 1963). The load sphere was placed on the occlusal surface of the mandibular left first molar to ensure that it would balance during testing. A resin (Pattern resin, GC America Inc, USA) transfer jig which covered the occlusal surface was made and attached to a metal rod held in the arm of the surveyor with resin (Figure 5.3). The transfer jig ensured that all the specimens were aligned and subsequently loaded identically. The epoxy die was cured in place with acrylic resin (MP2, Ortho-care Ltd., UK) in a silicone cylinder with a flat base.

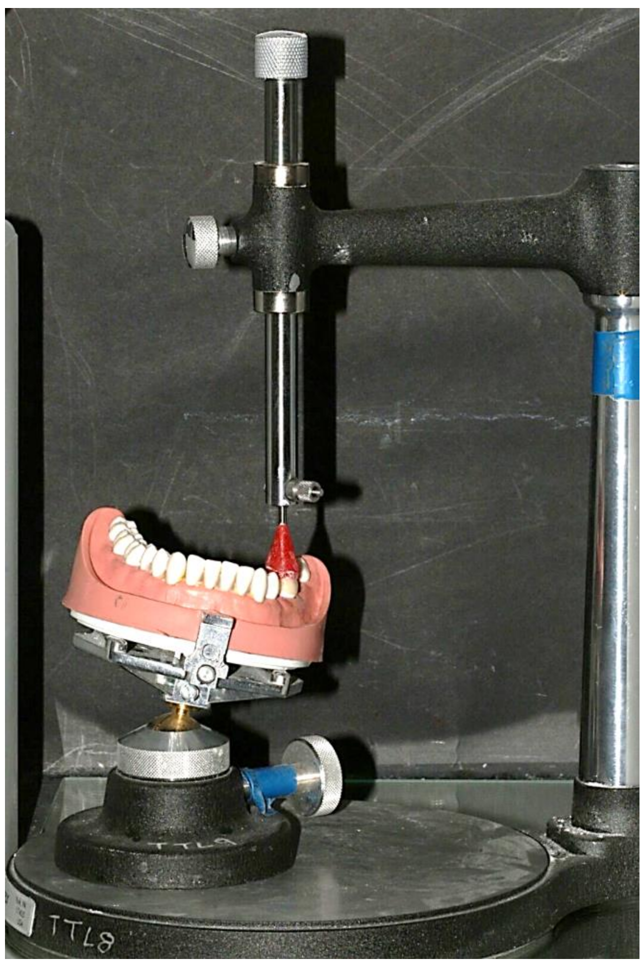
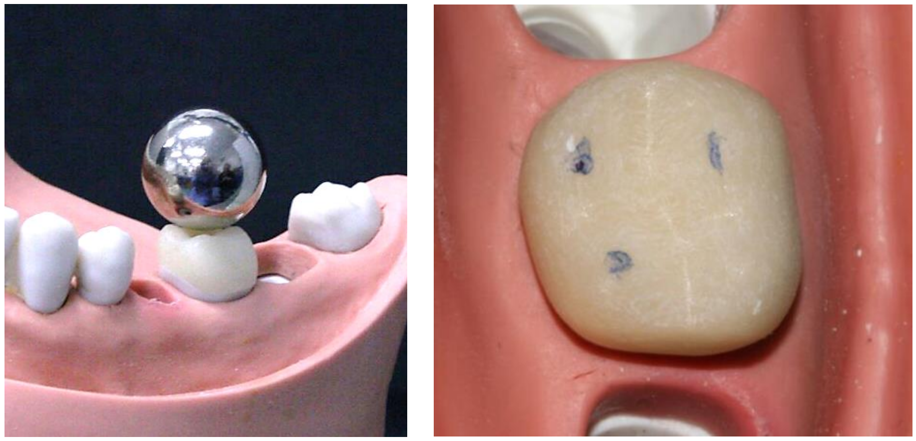


Figure 5.3 The occlusal plane of the mandibular model positioned as close as possible to 15 degrees laterally, a resin cap was attached to the rod in a surveyor, this 'tool' was used to transfer the orientation for each specimen.

5.2.6 Compression testing of the LDGC crown specimens

A large spherical hardened chrome steel sphere (Chromium AISI 52100 steel) with a diameter of 15 mm was positioned on the occlusal surface of the crown specimen and contacted the distobuccal, distolingual and mesiolingual triangular ridges of three cusps (Figure 5.4a)). The contact points (Figure 5.4 b)) between the crown and sphere were closer to the cusp tips than found in the ideal clinical scenario due to the high radius of curvature of the sphere, this ensured that during loading, contact would be on the ceramic only and not on the resin-ceramic junction of the repaired crown. A thin piece of non-rigid material (rubber dam) was placed between the chrome steel ball and the crown. An increasing force was then applied to the assembly using a tensometer (Instron, MA, USA) at a rate of 1.0 mm/min in a compressive mode until the material failed. A 5 KN load-cell was used with a load range of 50%. The load at failure was recorded for each specimen and the fragments collected for further analysis.



a) b)

Figure 5.4 a) 15 mm hardened chrome steel load sphere positioned on the occlusal surface of a LDGC crown specimen, the sphere contacts the distobuccal, distolingual and mesiolingual triangular ridges of these three cusps. b) contact points (blue) between the LDGC crown and sphere are more occlusally placed than found in the ideal clinical scenario due to the high radius of curvature of the load sphere, this ensured contact with the ceramic only and not the resin ceramic junction during loading.

5.2.7 Scanning Electron Microscopy (SEM)

The fractured fragments were examined visually. A representative specimen was randomly chosen from each unrepaired group (Group B and C) for closer inspection with SEM. The specimens were air dried and gold sputter-coated (Cressington Sputter Coater, 108 auto) at a thickness of 14 nm and then examined using a SEM (Zeiss Supra™ 65VP).

5.2.8 Statistical analysis

A minimum specimen size of n=15 was calculated by using a power analysis (power=0.8) with an effect size of 0.41 and a significance level of 0.05 (Appendix-Section 9.8). Analyses were performed using R statistical software (version 3.3.3) and corresponding packages: ‘fitdistrplus’ and ‘car’

(Delignette-Muller and Dutang, 2015). ANOVA was used to determine if there is a difference between group means, specifically for:

1) Examining the rhomboidal access cavity, one-way ANOVA tests were used to determine whether there was a difference in the mean failure load among groups A, B and D (Intact, unrepaired cavity and repaired cavity).
2) Examining the rectangular access cavity, one-way ANOVA tests were used to determine whether there was a difference in the mean failure load among groups A, C and E (Intact, unrepaired cavity and repaired cavity).
3) A two-way ANOVA was used to determine if there was a difference in mean failure load for both access cavity dimensions (rhomboidal and rectangular) and repair status (unrepaired and repaired with RC)

Assumptions for ANOVA were tested using Levene's test for homogeneity of variance and Shapiro-Wilkes test for normality. Post hoc Tukey HSD multiple comparisons of the means were performed using a 95% family-wise confidence level.

Weibull statistics (Weibull, 1951) were carried out for the data using the Weibull cumulative probability function given as:

$$\mathrm{P}f = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_{\theta}}\right)^{\mathrm{m}}\right]$$

Where, P*f* = the probability of failure, *m* = shape parameter (Weibull modulus) and σ_θ = scale parameter (characteristic strength). Maximum likelihood estimation (MLE) was used for parameter estimation, MLE increase the accuracy of confidence intervals compared with linear regression analysis (Quinn and Quinn, 2010). The Weibull modulus (*m*) is reflective of the scatter in the data, the characteristic strength ($\sigma\theta$) reflects the mean strength at which 63.2% of specimens will fail (Quinn and Quinn, 2010). The 95% confidence limits for the groups were calculated and differences were considered significant when no overlap occurred.

5.3 Results

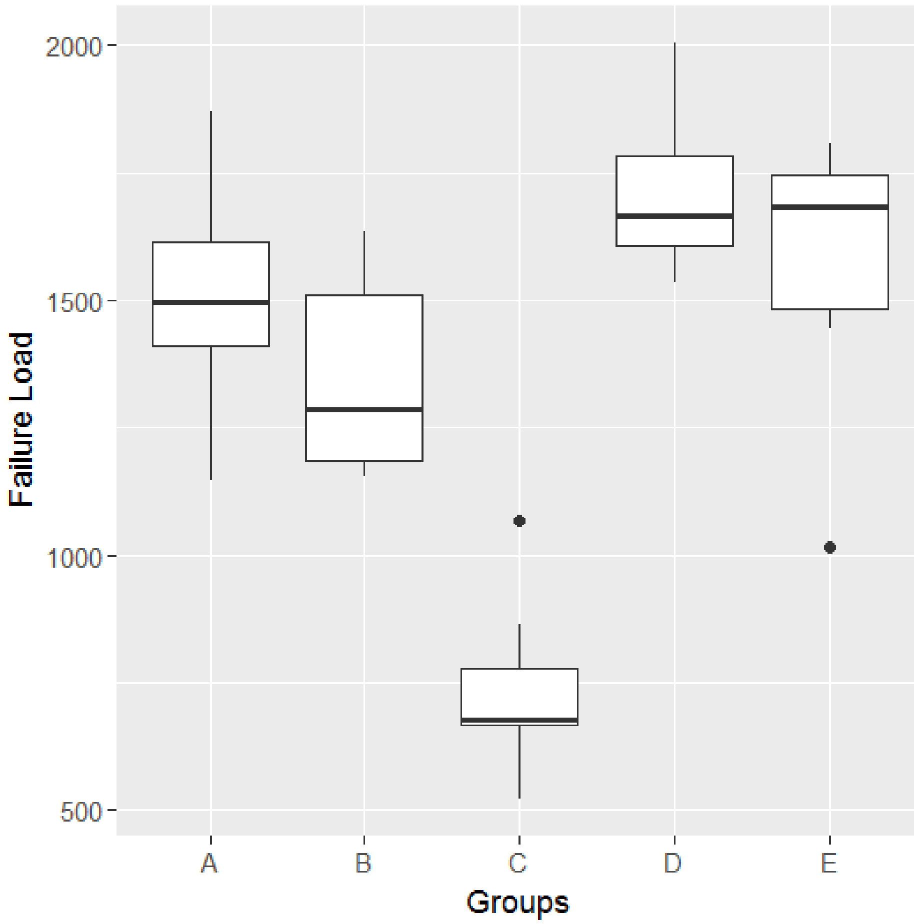


Figure 5.5 Descriptive statistics of failure load (N) including median, interquartile range and standard deviations for the dataset with pre-test failures removed, n=variable for each Group. Total missing values = 15. Group A, intact crown. Group B, unrepaired rhomboidal access cavity. Group C, unrepaired rectangular access cavity. Group D, repaired rhomboidal access cavity. Group E, repaired rectangular access cavity.

The mean load to failure values and the upper and lower confidence limits of the mean are given in Table 5.2 and displayed in Figure 5.5. Evidence of a single crack appeared in some specimens prior to testing (n=13), 100% of the cracks were identical in location which emanated from the distal-buccal margin towards the occlusal surface (Figure 5.6). These specimens were considered pre-test failures (PTF's) and noted to have occurred after storage (n= 9), or mounting in acrylic resin (n= 4). Failure of the acrylic resin base during testing also occurred (n= 2). The PTF's (n= 15) were excluded from the dataset for statistical analysis. No adhesion occurred between the crowns and the die substrates.

Group	min	max	mean	SD	median	IQR	Number of observations	Pre-test failures removed
A	1146.1	1869.8	1506.2	171.7	1496	202.1	14	1
B	1153.5	1634.8	1352.2	201.2	1285.1	326.8	7	8
C	523.2	1067.2	722.3	133.2	677.5	108.7	15	0
D	1533.2	2004.4	1710.8	159.2	1664.9	175.6	12	3
E	1017.2	1806.9	1598.7	223.4	1682.2	262.7	12	3

Table 5.2 Descriptive statistics of failure load (N) including mean, median, interquartile range and standard deviations for the dataset with pre-test failures removed, n=variable for each Group. Total missing values = 15.

Figure 5.6 An example of a specimen after removal from storage in water at 37°C exhibiting a crack initiated at the distal buccal margin of the LDGC crown and propagated toward the distal cusp on the occlusal surface.

One-way ANOVA tests were carried out to compare Group A, B, D (Table 5.3). Tests for normality (Shapiro-Wilkes, $W=0.97$, p-value=0.37) and homogeneity of variance (Levene's test, $F=0.35$, $DF=2$, p-value=0.71) were satisfied and the data considered parametric. Post-hoc Tukey HSD multiple comparisons of the means (Groups B-A, D-A, D-B) using a 95% family-wise confidence level was performed (Table 5.3). This showed significant differences between Groups D-A ($p=0.01$) and D-B ($p<0.001$) but not Group B-A ($p=0.15$).

Comparisons	Difference	Lwr	Upr	P adj	Sig
Groups B-A	153.92	- 352.12	44.29	0.15	
Groups D-A	204.65	36.21	373.09	0.01	*
Groups D-B	358.57	154.93	562.20	0.0004	*

Table 5.3 Results from post hoc Tukey HSD analysis for multiple comparisons of means for Groups A, B, D, 95% family-wise confidence level. Comparisons marked with * are significant.

One-way ANOVA tests were carried out to compare Group A, C, E (Table 5.4). Tests for normality (Shapiro-Wilkes, W=0.95, p-value=0.06) and homogeneity of variance (Levene's test, F=0.71, DF=2, p-value=0.5) were satisfied and the data considered parametric. Post-hoc Tukey HSD multiple comparisons of the means (Groups C-A, E-A, E-C) using a 95% family-wise confidence level was performed. (Table 5.4). This showed significant differences between Groups C-A (p<0.001) and E-C (p<0.001) but not for Group E- A (p=0.39).

Comparisons	Difference	Lwr	Upr	P adj	Sig
Groups C-A	-783.86	-943.59	-624.12	0.0	*
Groups E-A	92.56	-76.54	261.66	0.39	
Groups E-C	876.41	709.94	1042.89	0.0	*

Table 5.4 Results from post hoc Tukey HSD analysis for multiple comparisons of means for Groups A, C, E, 95% family-wise confidence level. Comparisons marked with * are significant.

A two-way ANOVA test was carried out to compare Groups B, C, D, E (Table 5.5). Tests for normality (Shapiro-Wilkes, W=0.95, p-value=0.05) and homogeneity of variance (Levene's test, F=0.68, DF=3, p-value=0.57) were satisfied and the data considered parametric. Post-hoc Tukey HSD multiple comparisons (Groups B-C, E-C, D-C, E-B, D-B, D-E) of the Group means using a 95% family-wise confidence level was performed (Table 5.5). This showed significant differences between all Group comparisons with the exception of Groups D-E. The null hypotheses for a), b) and for c) were rejected.

Comparisons	Difference	Lwr	Upr	P adj	Sig
Groups B-C	629.94	412.94	846.94	<0.01	*
Groups E-C	876.41	692.81	1060.02	<0.01	*
Groups D-C	988.51	804.9	1172.11	<0.01	*
Groups E-B	246.47	21.01	471.94	0.03	*
Groups D-B	358.57	133.10	584.03	0.001	*
Groups D-E	112.09	-81.44	305.63	0.42	

Table 5.5 Results from post hoc Tukey HSD analysis for multiple comparisons of means for Groups B, C, D, E using a 95% family-wise confidence level. Comparisons marked with * are significant.

The outcome from the Weibull analysis of the data including 95% confidence intervals are presented in Table 5.6. The characteristic failure load for the data followed the same ranking as the results from the post-hoc Tukey HSD analysis. Comparisons of Group means showed statistically significant differences (A-D, A-C, B-D, B-C, B-E, D-C) from each other, however Groups A-B, A-E, D-E were not statistically different. The Weibull modulus (*m*) for the intact crowns (9.5 (5.9-13.1)) was reduced with the preparation of a rhomboidal (7.8 (3.3-12.3)) and rectangular (5.4 (3.5-7.3)) access cavity, the modulus increased when the rhomboidal (11.0 (6.4-15.6)) and rectangular (11.2 (5.7-16.6)) access cavity were restored with RC.

Group	Weibull modulus (shape parameter)	95% CI	Characteristic strength (Weibull scale parameter)	95% CI	Number of Observations
A	9.5	5.9, 13.1	1580.4	1488.0, 1672.8	14
B	7.8	3.3, 12.3	1436.0	1291.9, 1580.0	7
C	5.4	3.5, 7.3	777.6	700.2, 855.0	12
D	11.0	6.4, 15.6	1784.3	1686.8, 1881.9	15
E	11.2	5.7, 16.6	1680.6	1592.1, 1769.01	12

Table 5.6 Weibull shape (modulus) and scale (characteristic strength) parameters including 95% confidence intervals for the dataset with pre-test failures removed, n=variable for each group. Total missing values = 15.

5.3.1 SEM

SEM images show the intricate microstructure of the fractured LDGC material (Figure 5.7) the coarse damage from the trephined endodontic access cavity is also evident (Figure 5.7, 5.8). A void is evident in the resin composite luting cement, a fracture in the cement occurred from the corner of this void (Figure 5.9).

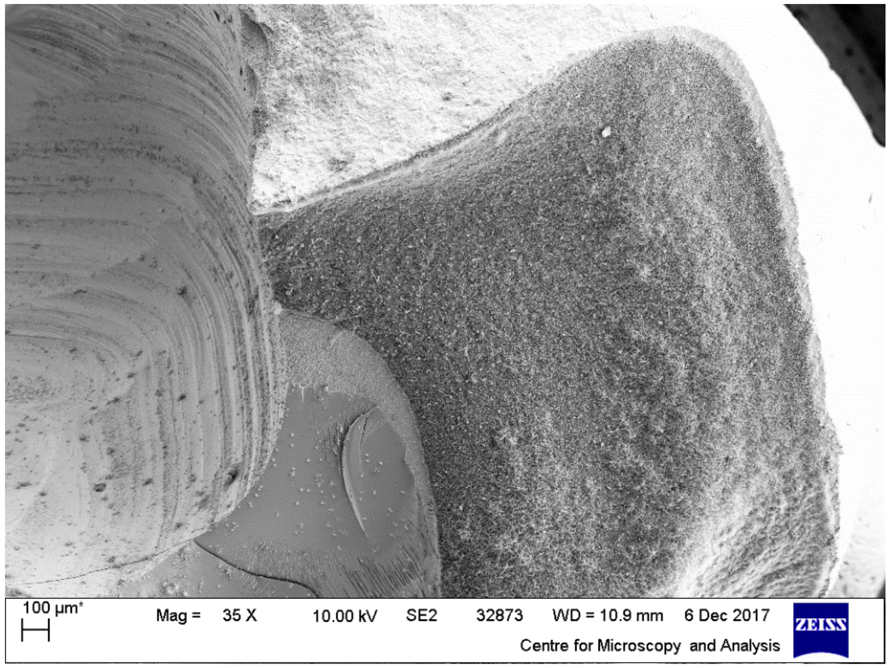


Figure 5.7 SEM (× 35) exhibiting the fractured surface of a LDGC crown with a rectangular endodontic access cavity.

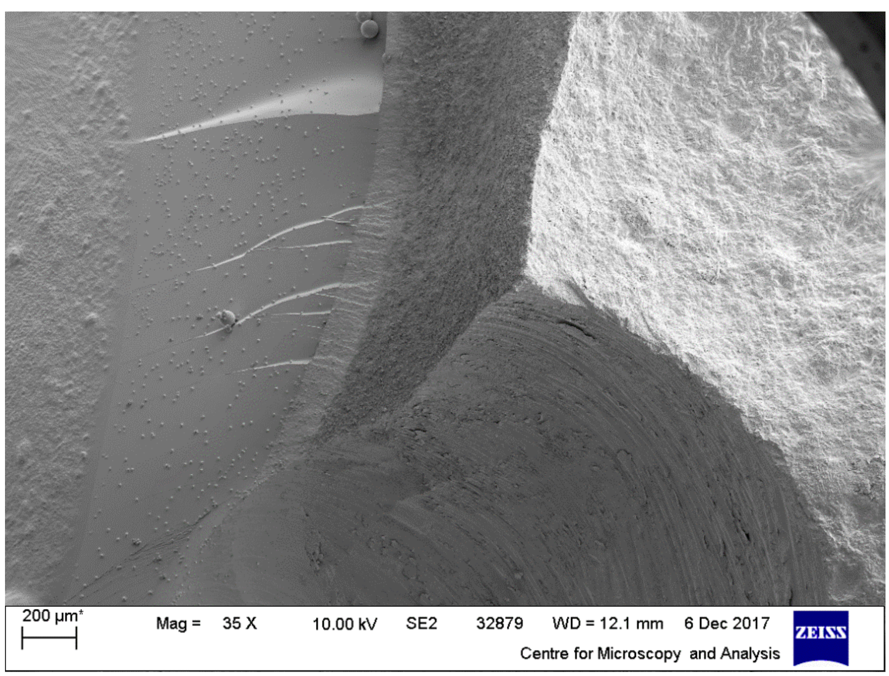


Figure 5.8 SEM (× 35) exhibiting the fractured surface of a LDGC crown with a rhomboidal endodontic access cavity.

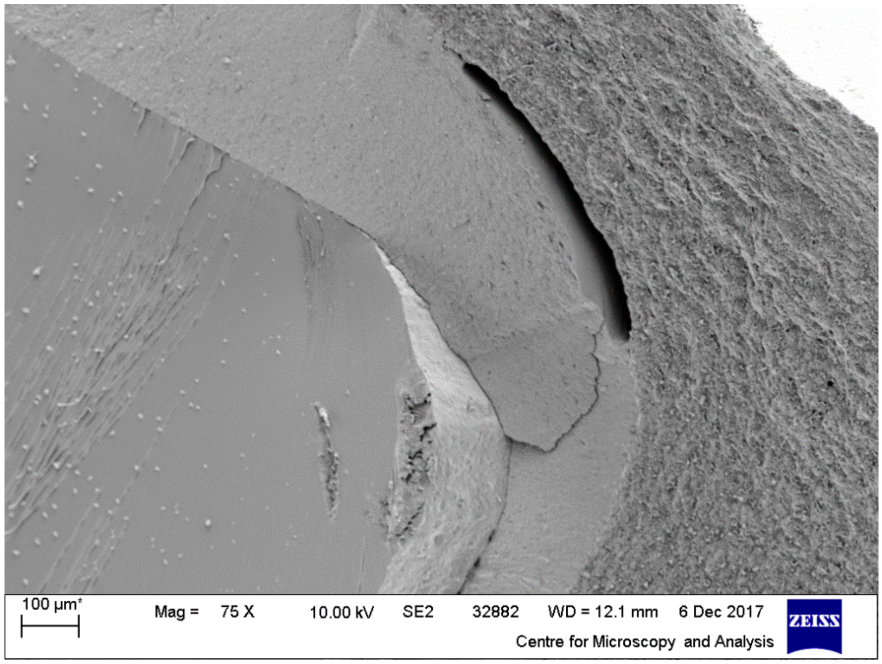


Figure 5.9 SEM (× 75) exhibiting the fractured surface of a LDGC crown with a rhomboidal endodontic access cavity. Note the void in the resin composite luting agent and the fracture emanating from the corner of the void to the die substructure.

5.4 Discussion

A rectangular access cavity is recommended to access and perform endodontic treatment when four canals are present in the mandibular first molar roots (Wilcox, 2015). Within the limitations of the current study, it has been shown that when a rectangular access cavity is prepared through existing LDGC crowns (Group C) a significantly ($p<0.001$) different mean failure load (722.3 ± 133.2 N) is found compared with the intact crowns (1506.2 ± 171.7 N). The failure load was regained when the access cavity was repaired (1598.7 ± 223.4 N) with a RC material and was comparable to that of the original intact crown. The result is an interesting finding and warrants further investigation. The effect of preparation of either cavity dimension resulted in a reduction in reliability, i.e. the Weibull modulus decreased. An increase in Weibull modulus was observed when the access cavities were repaired, while this effect seems clear, it should be noted that the number of observations are less than ideal (30) for a Weibull analysis (Quinn and Quinn, 2010) most notably in Group B after the pre-test failures were removed.

The high values obtained for failure load (1598.7 ± 223.4 N) in the current study are in excess of the maximum bite force values found intraorally (Tortopidis *et al*., 1998), but similar to those in another study (Bompolaki *et al*., 2015) and less than in one study (Qeblawi *et al*., 2011) for LDGC crown materials. It is not possible to directly compare values for failure load between studies since failure load is a measure of force required to fracture a material relative to the conditions under which it is tested. Conditions as close to those found clinically should be used to produce meaningful results (Kelly, 1999). Clinically realistic crown shape, tooth type and clinically relevant access cavities (Johnson and Williamson, 2015) were employed in the current study. Similarly, maxillary central incisors (Stokes *et al*., 1988) and maxillary first molars (Qeblawi *et al*., 2011) were investigated with standard recommended access cavity designs. Representative molar sized crown replicas devoid of occlusal anatomy and variation were employed elsewhere (Wood *et al*., 2006, Bompolaki *et al*., 2015). Previous investigations (Stokes *et al*., 1988, Wood *et al*., 2006, Qeblawi *et al*., 2011, Bompolaki *et al*., 2015) failed to control for and isolate the variables which concluded that the repair of an access cavity was responsible for the high failure loads obtained, comparable to those of the intact crown equivalents.

Fractures which originate from the cervical margins have been identified as an important mode of failure in many all-ceramic crown systems, thin walled crowns are particularly prone to this failure mode and is most notably a predominant failure mode for LDGC crowns (Nasrin *et al*., 2017). This specific failure type is attributed to hoop stress, which is generated through axial loading of cylindrical shaped crowns. Interestingly, Hussien *et al*. (2016) reported that fractures which originated from the margin were predominantly found in crowns which had a screw access cavity, in contrast to intact crowns where the fracture origin initiated from the occlusal surface. Marginal cracks which were observed in PTF's after specimen mounting in the current study (n= 4) could be attributed to stress which developed as a result of heat generation and/or expansion from the exothermic reaction of the acrylic resin mount. Any water absorption by the epoxy resin die material may potentially cause expansion of the die which the thin ceramic walls did not have sufficient strength to resist crack formation, thus fracture propagation occurred as a response to stress alleviation.

A sequential approach from coarse to fine-grit instrumentation is recommended when making adjustments to ceramic materials as damage is related to the abrasive size of the bur used (Coldea *et al*., 2015). The effect of preparing an endodontic access cavity through a ceramic crown resulted in the glaze being broken, therefore the ceramic is no longer impervious to water and the problem of slow crack growth (SCG) (Gonzago *et al*., 2011) can begin on immediate contact, thus direct repair to eliminate moisture from the access cavity margins would seem prudent. The potential to etch and bond to RC place dental porcelain and glass-ceramic, in a unique category of dental restorative materials. The use of silane coupling agents further enhances chemical bonding between glass-ceramics and RC (Luthra and Kaur, 2015). The ability to etch and bond to LDGC is important since it would seal the endodontic access cavity and reduce the incidence of SCG. A RC luting agent may aid crown retention after endodontic treatment has been performed, this was incidentally identified as a problem in the Cohen and Wallace study (1991) and in other studies involving PFM's (McMullen *et al*.,1989) where restorations had been non-adhesively luted in the first instance. Storage conditions in the current study were possibly too short (3 weeks) to observe significant effects from SCG, which could explain why the failure load for the crowns with an unrepaired rhomboidal access cavity was comparable to that of the intact crowns. Clearly, the access cavity ratio to crown size was an important factor in the failure process. While failure loads comparable to the intact crowns were attained when endodontically accessed crowns with, both a rhomboidal and rectangular access cavity, were repaired with a RC, again this finding was limited to short term aqueous storage. Complex intraoral forces were not accounted for in the current study. It would be reasonable to predict the depreciation of failure load with accelerated ageing if degradation of the RC bond were to occur. It is unknown if the failure load of the repaired crown can be maintained intraorally in the long-term, thus more rigorous testing conditions which include thermodynamic loading may yield improved predictive results. Further studies which include long-term aqueous storage and thermodynamic loading are warranted. The incidence of clinical survival of all-ceramic crowns in retrospective studies could also elicit potentially useful information.

5.5 Conclusion

The null hypotheses were rejected. Preparation of a rhomboidal access cavity did not adversely affect the failure load of lithium disilicate glass ceramic crowns after short-term aqueous storage. Preparation of a rectangular endodontic access cavity in LDGC crowns demonstrated a significantly lower failure load compared with the intact crowns. Within the limitations of this study, it has been shown that failure load could be regained when a repair of the access cavity with RC was made.

Chapter 6

Endodontic Access Cavity Simulation in Ceramic Dental Crowns

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Endodontic Access Cavity Simulation in Ceramic Dental Crowns.

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Dental materials 2013 Jun;29 (6):626-34.

Abstract

Objective: It is proposed that a non-uniform rational B-spline (NURBS) based solid model of a ceramic crown would be a flexible and quick approach to virtually simulate root canal access cavities. The computation of strain components orthogonal to surface flaws generated during the drilling would be an appropriate way of comparing different access cavity configurations.

Methods: A µCT scan is used to develop a full 3-D NURBS geometric solid model of a ceramic crown. Three different access cavity configurations are created virtually in the geometric model and are then imported into proprietary finite element software. A linear analysis of each crown is carried out under appropriate *in vivo* loading and the results are post-processed to carry out a quantitative comparison of the three configurations

Results: The geometric model is shown to be a flexible and quick way of access cavity simulation. Preliminary indications are that post processed strain results from the finite element analysis are good comparators of competing access cavity configurations.

Clinical Significance: The generation of geometric solid models of dental crowns from µCT scans is a flexible and efficient methodology to simulate a number of access cavity configurations. Furthermore, advanced post-processing of the primary finite element analysis results is worthwhile as preliminary results indicate that improved quantitative comparisons between different access cavity configurations are possible.

6.1 Introduction

Classical structural mechanics fails to produce an adequate elucidation of the stresses and strains developed in a system as geometrically complex as a grinding tooth. Naturally, the boundary of such a surface cannot be described by a singular component such as a beam or a plate, and therefore a computer simulation must be carried out. All physical phenomena are modelled mathematically as partial differential equations. It is rare that the solutions for these partial differential equations are trivial (Saad, 2003), but since the development of the computer, numerical solutions are now mainstream. For boundary value field problems, including structural mechanics, the Finite Element Method (FEM) is the standard numerical approach. The ability of the FEM to accurately compute stress and strain fields has particular advantages in the field of restorative dentistry where an understanding of the deformation responses due to *in vivo* loading is of critical importance.

A very common procedure performed by dentists is root canal treatment (RCT). RCT is performed when the pulp becomes infected or damaged, causing pain to proliferate through the tooth. Indeed, this is such a common complaint that ‘root canal’ is a something of a vernacular synonym for serious discomfort and distress. Clinically, root canal pain is tackled by endodontic therapy, which involves any number of procedures that take place inside the tooth, the general principles of which have been traced as far back as 1826 (Grossman, 1976). Studies have shown that the side-effects of crown fabrication and installation can cause irreversible pulp necrosis (tissue death), which may consequently necessitate RCT. In fact, a 3% to 25% pulpal necrosis rate has been recorded in teeth with full coverage fixed restorations over an 18 to 25 month period (Kirakozova and Caplan, 2006). It is further estimated (Wood *et al*., 2006) that between 20% and 50% of all RCT is performed through complete coverage crowns (Goldman *et al*., 1992, Trautmann *et al*., 2000b).

6.1.1 Motivation

It has been known for quite some time (Teplitsky and Sutherland, 1985, Sutherland *et al*., 1989, Cohen and Wallace, 1991) that endodontic access itself can cause varying levels of distress to the crown due to subsequent *in vivo* loading. Flaws generated by the action of the drilling burs are hypothesised to ultimately develop into cracks and propagate causing failure in crowns. Recent studies have shown that the failure load of restorations post-access is independent of drilling implement or technique (Haselton *et al*., 2000, Qeblawi *et al*., 2011). Therefore, whether or not one selects a high efficiency diamond rotary cutting instrument or a tungsten carbide fissure bur has no appreciable effect, as some microcracks will form, regardless of the instrument. The clinician has control over the following: geometry, location, number of access cavities and the filling material. Research into these parameters has not been very active and provides the motivation for this work. If recommendations of optimal access cavity configurations, alongside a choice of filling material, could be formulated, they would be clinically useful. Currently, there is no conclusive body of research that has determined the correct restoration method and material; judgements based on the 3D modelling could effect change as it offers a wide scope relative to biomedical research, a field in which it may be either prohibitively expensive to or ethically questionable to test on *in vivo* or even *in vitro* samples (Magne and Tan, 2008).

6.1.2 Purpose

This paper aims to demonstrate that a non-uniform B-spline (NURBS) based solid geometric model of ceramic crowns is a flexible and quick approach to virtually simulate root canal access cavities. Furthermore, it is proposed that tensor strain components orthogonal to surface flaws, rather than scalar strain quantities, are an appropriate way of comparing access cavity configurations.

6.1.3 Paper summary

Section 6.2 will describe the development of the geometric model from a µCT scan of a representative dental ceramic crown and the virtual modelling of three different access cavity configurations. The geometric model is then imported into proprietary FE software, an *in vivo* loading scenario is applied and the results of the FE analyses are presented in Section 6.3. Section

6.4 discusses the effectiveness of the geometric modelling approach presented and presents some preliminary results of a strain based post-processing methodology that better predicts the long term effect of low intensity cyclic loading on the crown. The conclusions are detailed in Section 6.5.

6.2 Materials and Methods

In any Finite Element Analysis (FEA), there are four key factors that the analyst must consider in order to develop a sound model; geometry, material properties, loading and boundary conditions. To that end, the modelling methodology used in this work will be illustrated under these headings.

6.2.1 Geometry

6.2.1.1 Acquisition

For the purposes of this work, a representative sample ceramic crown was created using the lost-wax technique in the dental laboratory at the Cork University Dental School & Hospital. This crown is approximately 9.35 mm in width and 8.16 mm in height, and depicts the crown of a mandibular first molar, purposively selected as it is the most common tooth to undergo endodontic treatment (Wood *et al*., 2006, Zadik *et al*., 2008, Carrotte, 2011). This tooth was scanned by a Scanco® CT40 µCT device and the outputted data was saved in the scanner's native format.

6.2.1.2 Data Processing

A simple MATLAB® procedure converted the original data to the more commonly used DICOM (Digital Imaging and Communications in Medicine) format. Each µCT slice is a greyscale image, 1024 x 1024 pixels in size, and has a 16-bit colour depth. In total, 450 slices at a thickness of 0.02 mm were recorded amounting to approximately 950 MB of data. Therefore, to facilitate visualisation, a workstation with 16 GB of RAM operating on 64-bit Windows was used. It may be noticed that the data recovered from a µCT scan is raw and requires some basic image processing before 3D reconstruction is possible. In this work, all image processing and reconstruction work is undertaken in *3D Slicer*, an open source medical visualisation software package (Pieper *et al*., 2004, Pieper *et al*., 2006, ww.slicer.org, 3D Slicer).

The main point of a 3D reconstruction from µCT imaging is to identify the structures of interest from each slice and assemble these into a 3D model. This process is commonly referred to as segmentation and it refers to the conglomeration of all points on the µCT slice that are of interest into one cogent structure known as a label map, which is simply a binary image superimposed over the original slice. In essence, one is designating particular areas of the µCT image that they want to include in the resulting model as the label map(s) that are used to create the 3D visualisation. Note that there is the possibility of isolating several structures: one could simply create several label maps, based on areas of the slice of different radiodensity (the quality, which is analogous to corporeal, physical density). Commonly, dentists use µCT imagery to segment and create models encompassing all major structures in the tooth - enamel, dentine etc. This would be achieved by the use of several label maps. As this analysis is concerned with visualising a ceramic crown, only a single label map is required.

Like much image processing, segmentation is an iterative process, the results of the initial segmentation effort may be seen in Figure 6.1. Further refining is necessary, as it is quite clear that the result of this operation leaves a rather noisy image. It can be seen that the edge of the label map is quite rough and there are many isolated pockets of noise (known as 'islands').

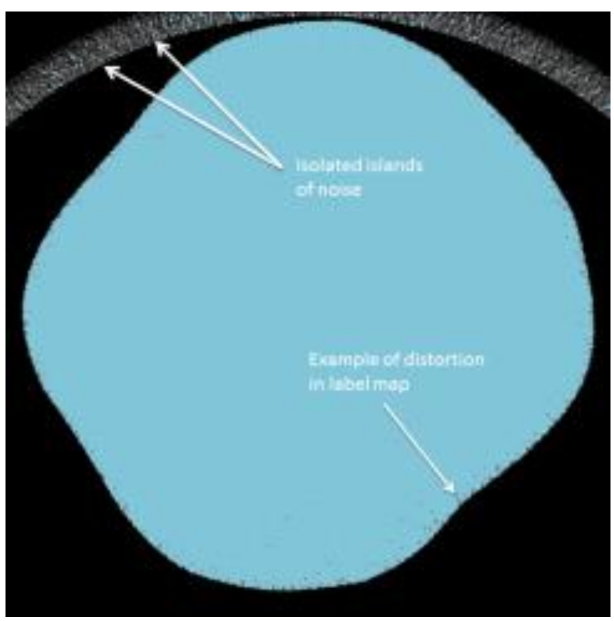


Figure 6.1. Initial segmentation of the µCT scan by 3D-Slicer. Note the "islands" of noise and the boundary distortions.

It is possible to edit the label map; using a combination of a Gaussian smoothing algorithm and island removal procedures, the image in Figure 6.2 may be achieved. Once a succinct and accurately smoothed label map is created, the model making process can be started.

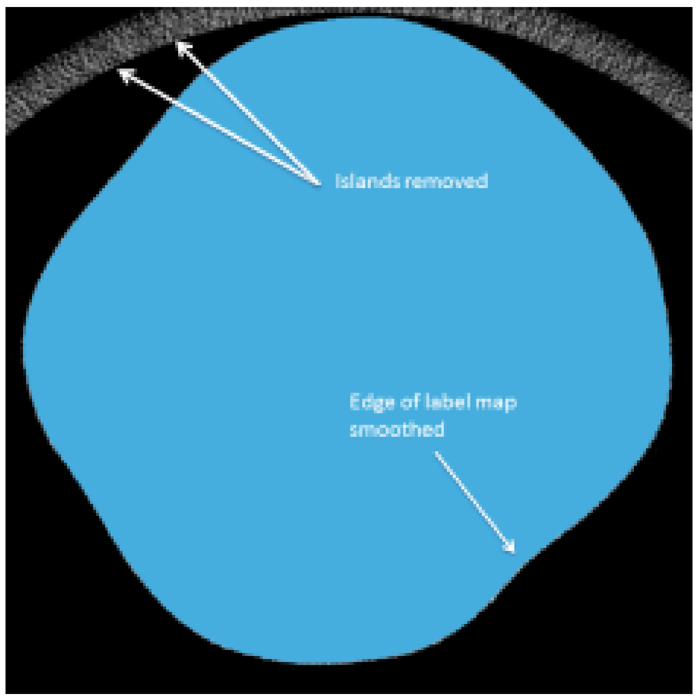


Figure 6.2. Improved µCT scan after Gaussian smoothing and island removal.

6.2.1.3 3D Reconstruction

3D Slicer builds the model by collating all the refined label maps and, running the Marching Cubes algorithm (Lorensen and Cline, 1987), it extracts a polygonal mesh from the isosurface created by the perimeter of the label map. Figure 6.3 shows a screenshot of the finished model in the *3D Slicer* software environment.

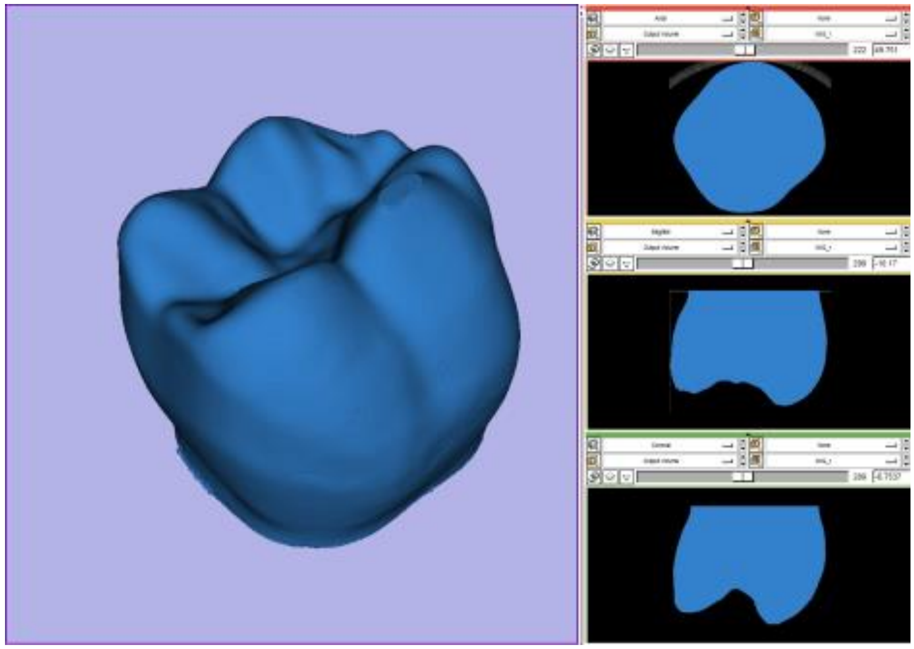


Figure 6.3. Screenshot of the finished model in the 3D-Slicer software environment.

Following model generation, some simple post processing options are available at this stage, including decimation and smoothing. Decimation reduces the number of triangles by averaging the shapes of several small triangles into one larger triangle, which is of importance in reducing the mesh density and, hence, file size. The finalised model is outputted as a Stereolithography (STL) file.

6.2.1.4 Parametric geometric model

The innovative step in this methodology was to move aside from the polygonal mesh to facilitate the creation of a realistic endodontic access cavity. By converting the polygonal mesh to a parametric model, it is possible to adapt the geometry in a convenient work environment such as *Autodesk Inventor*, (Autodesk Inventor Professional, San Raphael, CA, USA, 2012). There are many options of parametric model, but by far the most flexible and mainstream are non-uniform rational B-spline (NURBS) models (Piegl and Tiller, 1997). Most computer aided design (CAD) and finite element analysis (FEA) software can manipulate and import them. In order to do this, the surfacing feature of *Leios*® (3D3 Solutions, Leios, Burnaby, BC, Canada) (a reverse engineering meshing software) was used to 'wrap' an air-tight surface of stitched together NURBS patches over the original 3D polygonal mesh (Figure 6.4).

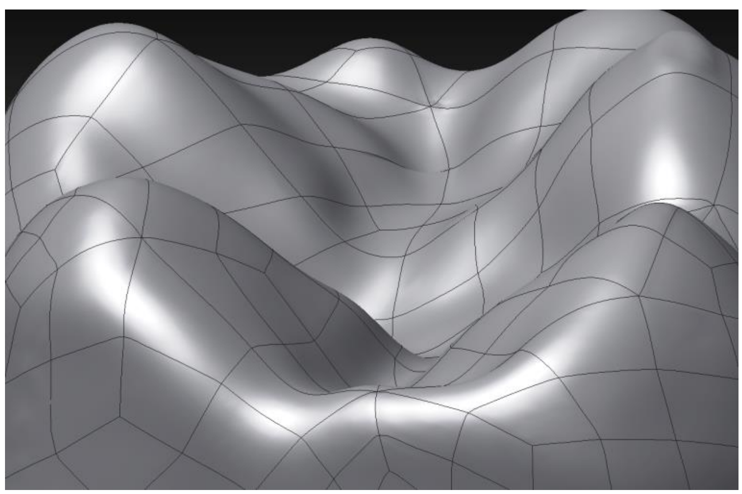
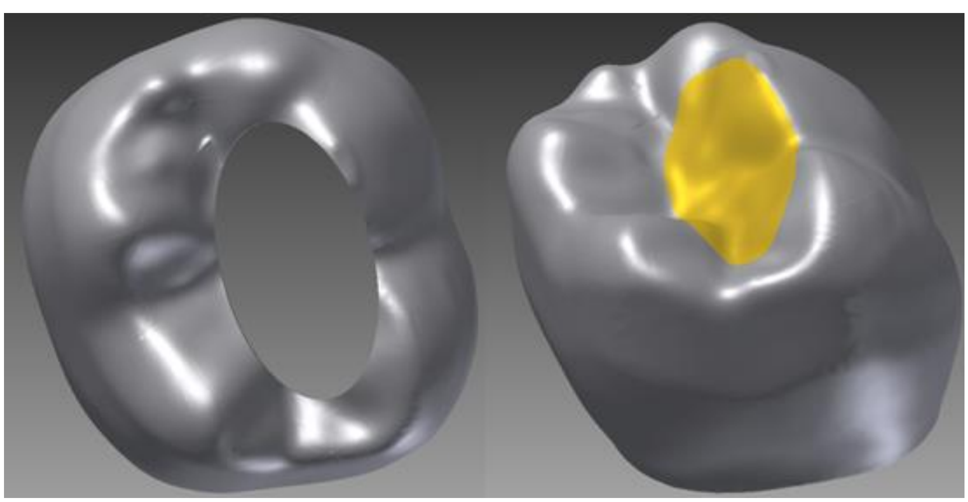


Figure 6.4. Occlusal surface of the ceramic crown geometrically modelled using NURBS patches.

This has a twofold benefit. Firstly, the geometry could be imported directly into the FEA software *Strand7*®, which takes advantage of the advanced automesher and can create a congruent surface mesh of quadratic, or 6 node triangles, followed by a solid mesh of 10 node tetrahedra which accurately reflect the surface geometry. Polygonal meshes from reconstructions are for visualisation purposes only, therefore 3 node linear elements (facets) suffice, however in an advanced FEA higher order elements are to be preferred (Zienkiewicz *et al*., 2005). The second benefit is that, once in this CAD format, a whole host of possibilities are opened up editing the geometry of the model while using a software system such as *Inventor*®.

Simple shapes; a rounded rectangle, an ellipse and two small loops were sketched in 2D and copied with each copy placed on either end of the tooth model (top and bottom). Using a loft method, a smooth continuous object was created, which formed the geometry of the access cavity and filling. A combination of the Boolean operations (subtract and add) was applied, which first cut the access cavity and subsequently re-filled the model with a separate solid object. This is demonstrated in Figure 6.5.



(a) **(b)**

Figure 6.4. Access cavity generated by lofting the 2D shape through the crown solid model. (a) Generated elliptical cavity and (b) the resulting combined ceramic crown and filled cavity.

6.2.1.5 FE Mesh

The final geometry, including the endodontic access, was saved and exported as a step (STP) file, which is a CAD file format which is best suited to this sort of solid modelling as it stores different materials in a way that *Strand7* can easily separate. Upon importing the geometry, a default clean was performed: this is worthwhile, as any small disconnections, imperceptible in the CAD environment, need to be seamed together (Adams and Askenazi, 1998) and overall connectivity will be checked, a point emphasised by Magne (2010). The same FE meshing process is applied as described previously in that a surface mesh is developed, followed by a solid element mesh.

At this juncture, it is important to interrogate the model to assess its quality, as visual inspection alone may not be enough to verify the competence. Of critical importance to solid meshes are the aspect ratio, which may be assessed by computing the determinant of the Jacobian matrix (Zienkiewicz *et al*., 2005) and the dihedral angle ratio of each solid element. Decisions to manually adapt the mesh or entirely re-mesh, refining problematic areas, can be better informed by using the checks mentioned. That being said, in meshes of this size (circa 60,000) and complexity it is unlikely that every element will be perfect; in the present case, it may be attributed to the curved nature of the crown, where high aspect ratios and large curvatures are unavoidable. However, the global performance of the mesh will not be hampered by a sporadic spurious element.

It must be noted that meshing geometric solid models is still a laborious and iterative process, but is potentially more accurate and useful than the current methods of FE mesh generation of CT generated models, as described in the literature. As demonstrated here the generation of a number of significantly different access cavity geometries is easily achieved with the solid model using standard Boolean operations.

6.2.2 Material properties

The analyses in this study simulates the dental ceramic, *IPS e.max® Press* (Ivoclar Vivadent, 2014) and filling composite *Tetric EvoCeram®* (Ivoclar Vivadent 2011), both manufactured by Ivoclar Vivadent. This material has been examined previously by Qeblawi *et al*. (2011) (Table 6.1).

Material properties	IPS e.max® Press	Tetric EvoCeram®
Young's modulus (GPa)	95	10
Poisson's ratio	0.234	0.25
Density (g/cm^3)	2.1	1.7

Table 6.1. Material properties of the crown ceramic, IPS e.max® Press and the filling composite Tetric EvoCeram®, both manufactured by Ivoclar Vivadent.

6.2.3 Loading

The models in this paper were assessed in a manner reflective of *in vivo* loading conditions. The manner in which FE models of teeth are loaded is a question of some debate, but there are two main approaches: some researchers tend to simulate laboratory experiments (Magne, 2010) and others aim to mimic the *in vivo* environment (i.e. the general loading applied by the dental forces) (Dejak *et al*., 2003, Rodrigues *et al*., 2009).

In a recently published work, Qeblawi *et al*. (2011) studied the effect of endodontic access on, all-ceramic restorations (a lithium disilicate glass ceramic, similar to the dental ceramic in this study). Several crowns of different ceramics were manufactured and subsequently endodontically accessed. Loaded with a hemispherical indenter, driven by a piston, they found that the crowns could withstand direct loads of up to 2354 ± 476 N.

Conventional and clinical knowledge immediately refutes this as occlusal forces never reach such a figure. Maximum forces approach 800N with the average bite force lying somewhere around 200 ± 50 N (Hattori *et al*., 2009). Ausiello *et al*. (2011) follow this protocol and apply a loading condition based on a similar experiment, i.e. two 300 N point loads at 35° to the vertical at pre-specified locations.

However, the use of point loads is disputed by Benazzi *et al*. (2011), who suggest that such an approach constitutes an over-simplification. The point load creates a singularity in the stress tensor at the location of the load application, which will manifest itself in a linear FEA as an artificially high stress concentration, which will tend to drive the analyst to refine the mesh, increasing mesh density in the vicinity of the applied point load. Indeed the process of refining throws up several further unnecessary complications which are to be avoided. It is felt therefore that this type of loading does not seem to be an appropriate reflection of actual behaviour; a point that is underscored by Kelly (1999), who insists that for laboratory tests, and FEA by extension, to be relevant, they need to replicate the damage caused in clinical failure. Crucially, tests which create damage uncharacteristic of clinical situations can be a misleading guide to clinicians.

Therefore, this analysis does not mimic the setup of a laboratory experiment but rather follows the more realistic approach set out by Dejak *et al*. (2003) and Rodrigues *et al*. (2009), who apply a general pressure over the occlusal surface simulating a masticatory or chewing action (the hypothesis is that food being grinded by teeth would cover the occlusal surface, hence creating a uniformly distributed load). By applying such a load, i.e. a pressure which results in a normal reaction force of 200 N, an accurate simulation of *in vivo* loading conditions is achieved.

6.2.4 Boundary conditions

Boundary conditions for this analysis are simple – fixity or zero displacement for all nodes on the bottom surface and bottom edge of the crown, simulating the behaviour of the crown at the cementoenamel junction. This is standard practice in current simulations and is not disputed (Ausiello *et al*., 2001, Dejak *et al*., 2003, Magne, 2010, Benazzi *et al*., 2011).

6.3 Results

The results of the linear static FE analysis, Von Mises stress and maximum principal strain are presented in this section.

6.3.1 Von Mises Stress

Contour plots of the Von Mises stresses are shown in Figure 6.6. Each image is taken from the same angle; a plan view of the occlusal surface. Note that the filling composite has been removed for the sake of clarity.

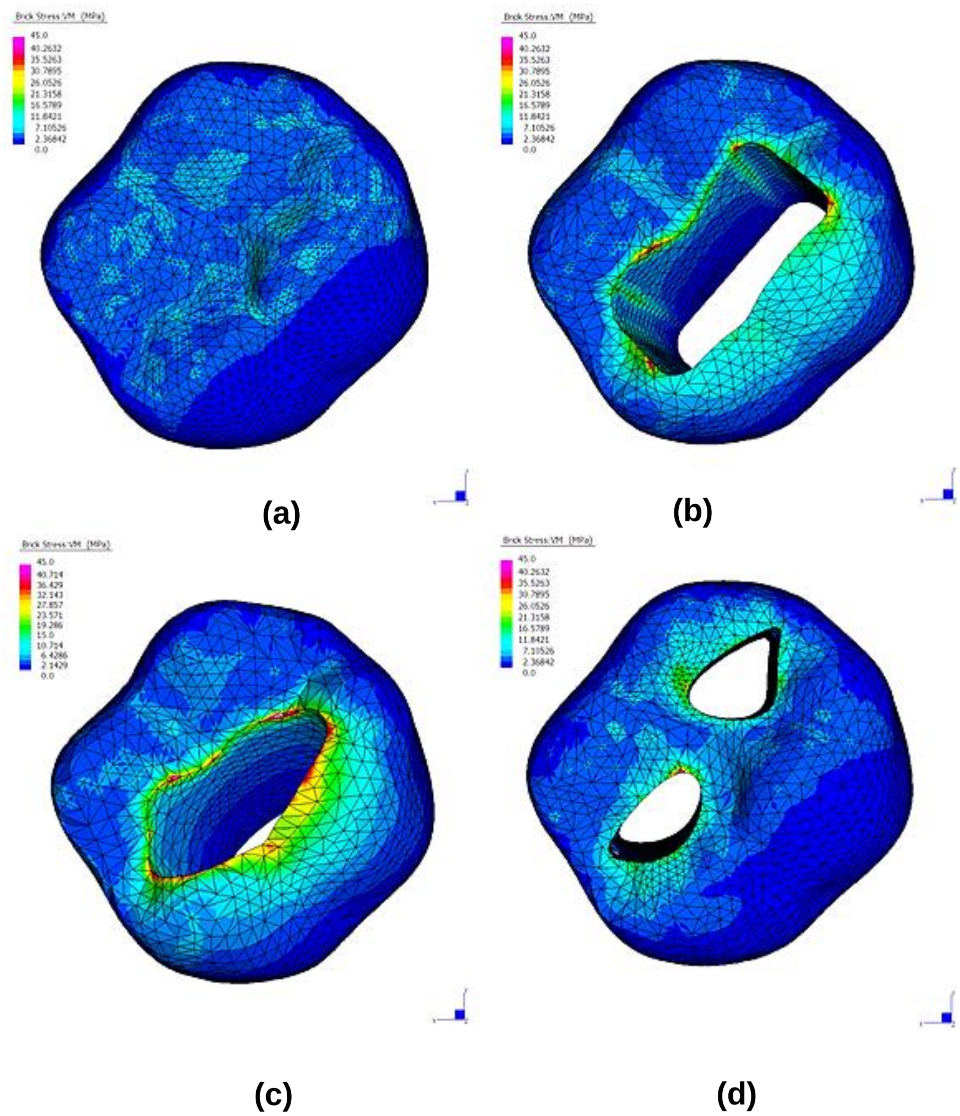
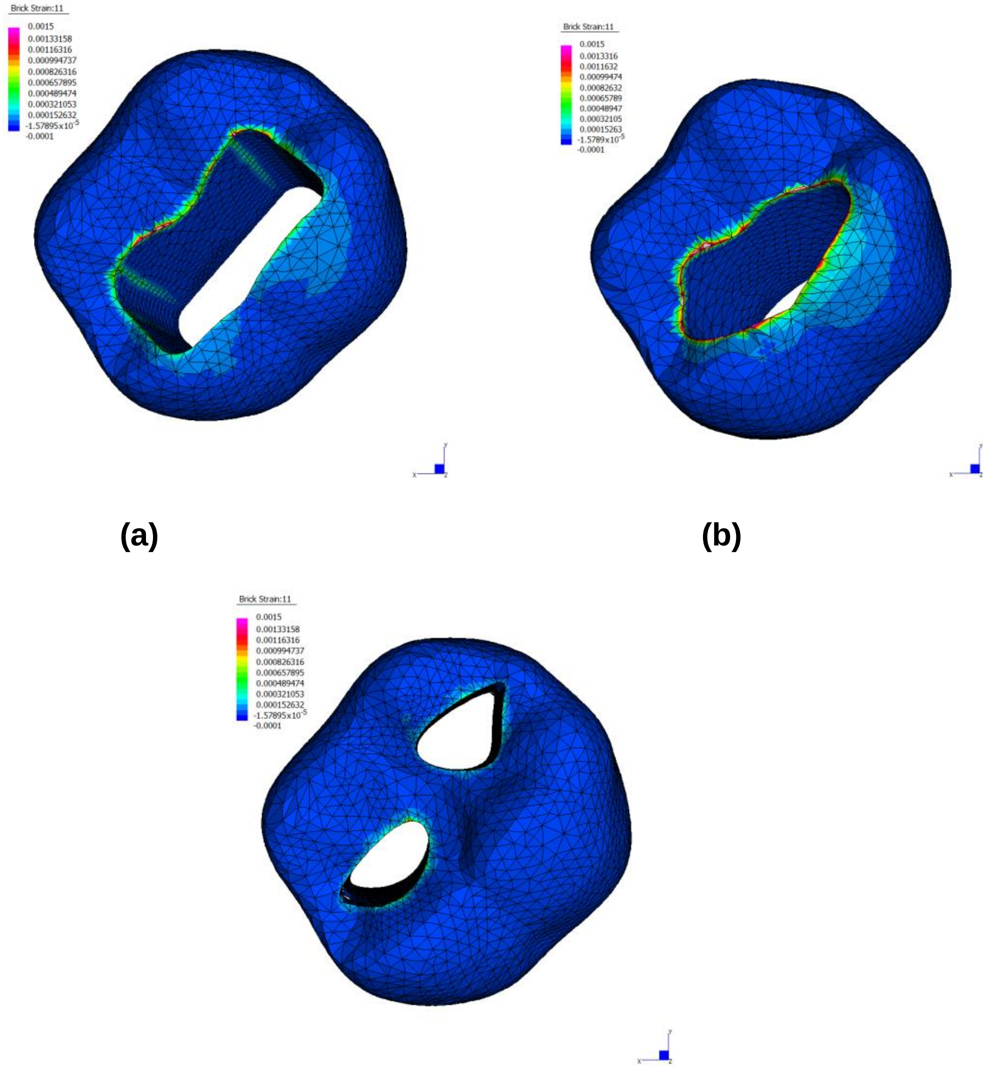


Figure 6.6. Plots of the von Mises stress distributions for (a) intact crown; (b) rounded rectangluar access cavity; (c) elliptical access cavity and: (d) double access cavity.

6.3.2 Maximum principal strains

Contour plots of the maximum principal strains (ϵ_{11}) are presented below (Figure 6.7) for consideration. As with the Von Mises plots above, each image is taken from the same angle and the filling composite has been removed for the sake of clarity.



(a) **(b)**

(c)

Figure 6.7. Contour plots of the maximum principles stress (σ_{11}) for the (a) rounded rectangular access cavity, (b) elliptical access cavity and (c) double access cavity.

6.4 Discussion

It has been known for quite some time (Teplitsky and Sutherland, 1985, Sutherland *et al*., 1989, Cohen and Wallace, 1991) that endodontic access itself can cause varying levels of distress to the crown – prior to installation and subsequent loading. In this study it is hypothesised that flaws generated by the action of the drilling burs ultimately develop as cracks and propagate causing failure in crowns (Figure 6.8). Recent studies have shown that the failure load of restorations post-access is independent of drilling implement or technique (Haselton *et al*., 2000, Qeblawi *et al*., 2011) leading to the conclusion that any access work will reduce the restoration lifespan. However, from linear fracture mechanics, the optimal cavity shape that reduces tensile strains normal to imperfections will positively affect the lifespan of the crown.

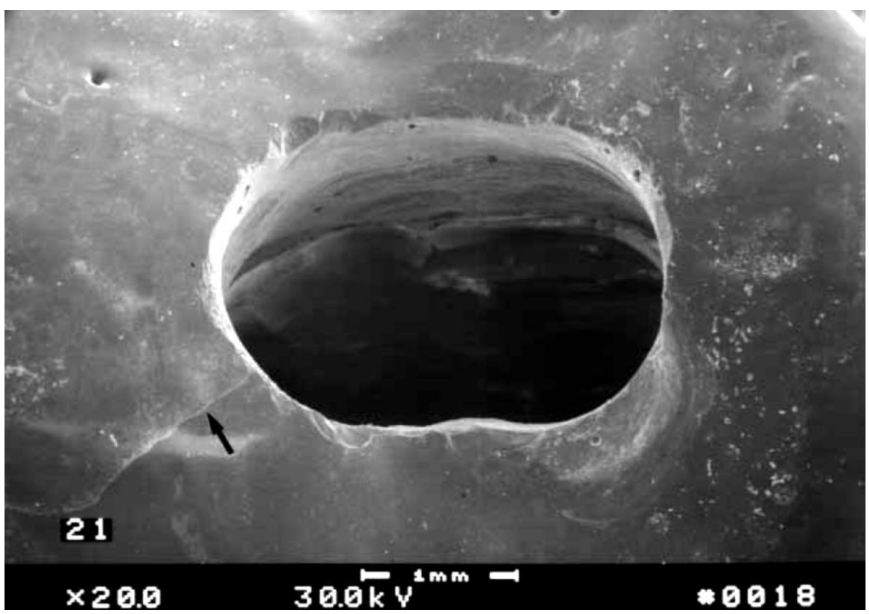


Figure 6.8. Example of a microcrack in an access cavity formed using diamond bur (Haselton *et al*., 2000).

6.4.1 Von Mises Stress

Von Mises stresses are a material failure based combination of the three principal stresses, σ_{11}, σ_{22} *and* σ_{33}. The maximum value for Von Mises stress in any of the four meshes was 58 MPa, recorded in an element on the surface boundary of the rectangular access. This figure alone is far lower than the currently accepted value for biaxial flexural strength, 440 ± 55 MPa (Albakry *et al*., 2003). This suggests that material failure would not occur at such a low load.

However clinical observations overwhelmingly point towards failure of crowns at general in-vivo occlusal loads (Kelly, 1999) due to fatigue generated crack propagation from the crown-filling interface. As von Mises is by definition a positive scalar quantity, it does not differentiate between a positive scalar quantity, it does not differentiate between compressive and tensile stresses or principle directions. It is proposed here that a better approach is to consider tangential principle strains/stresses at the ceramic/filler interface. This presents a valid case for not using the findings of failure theories to predict crown life spans.

6.4.2 Principal Strains

A visual investigation of the principle strains developed at the access interface shows that, in general, principal tensile strains tend to be orientated on an axis normal to the ceramic-filler interface (Figure 6.9). Therefore, the other two strain components are tangential to the interface surface.

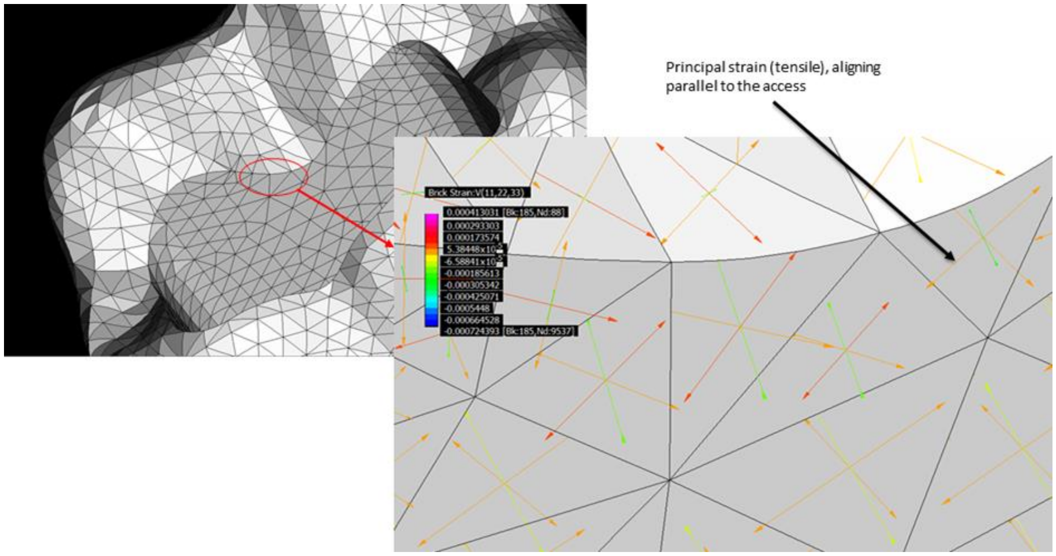


Figure 6.9. Vector plot illustrating the direction and magnitude of principal strains at a typical location on the ceramic/filler interface.

It is felt that it is these tensile strains that are of critical importance to the study. Flaws observed post-drilling seem to be perpendicular to the opening (Figure 6.9), therefore a tensile strain orthogonal to this flaw would likely exacerbate it. Considering that logic, the six recovered Cartesian strain components for each node along the ceramic/filler interface were manually retrieved for the FEA results' file. The nodal coordinates for the sampled nodes were also retrieved. Using this information, the tangential vector could be computed from the nodal positions and then the six strain components could then be combined to determine the strain component in that tangential direction. Figure 6.10 clearly shows the concept. Since this strain is both signed (i.e. a positive strain is tensile and a negative strain is compressive) and, by definition, orientated orthogonal to any possible flaw in the ceramic, then it is possible to infer if it will exasperate the flaw. This process is applied to each of the three access cavity scenarios and a plot of this strain component around the external circumference of the proposed access cavities is shown in Figure 6.11.

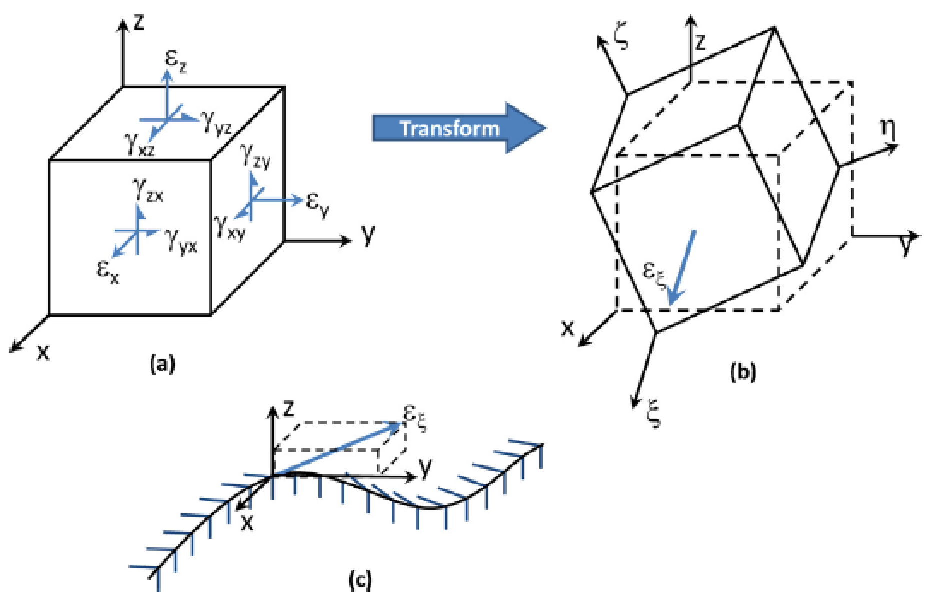


Figure 6.10. **Transformation of the Cartesian strains, $(\epsilon_x, \epsilon_x, \epsilon_x, \lambda_{xy}, \lambda_{yz}, \lambda_{zx})$, to a strain component, ϵ_ξ, along the ceramic/filler interface edge.**

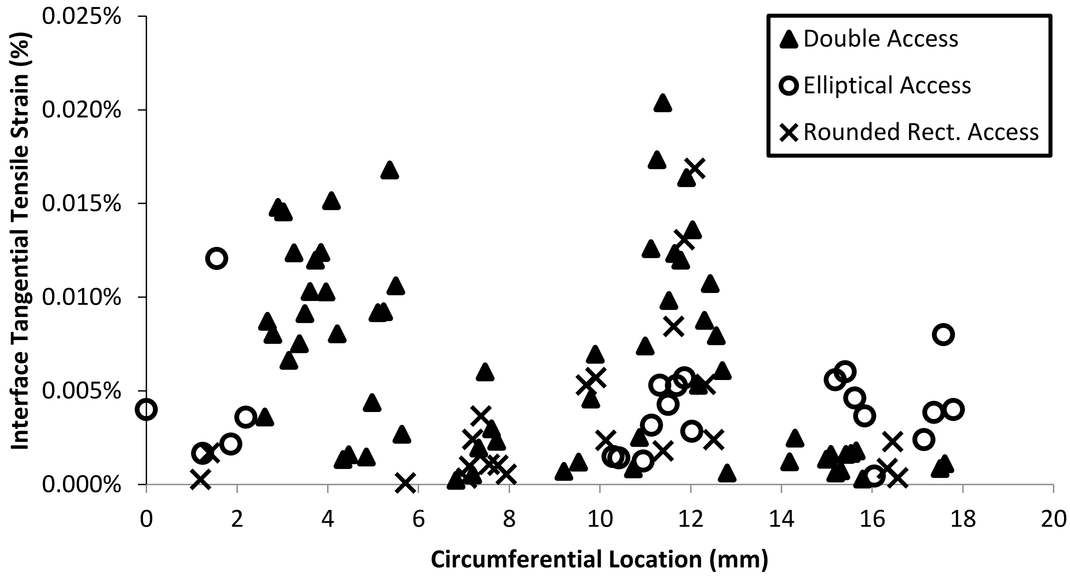


Figure 6.11. The tensile tangential component of strain, ϵ_ξ, along the ceramic/filler interface for each of the proposed access cavity scenarios.

A cursory glance would indicate that the optimal configuration of the three access cavities proposed here would be the single elliptical access. This is because this configuration results in the lowest value of peak tensile stress. Furthermore it also contains fewer higher strains than the other two configurations. This result is consistent with current clinical practice of avoiding sharp corners and or small radii of curvature in drilled cavities.

6.5 Conclusion

This paper presents a methodology for the development of a NURBS solid model of a ceramic crown, from a µCT scan that allows easy construction of virtual access cavities, typical of root canal treatment post installation of the crown. Three cavity configurations are created on the solid model, demonstrating the methodology's flexibility. These geometric models are then imported into proprietary FE software and meshed, loaded appropriately to accurately simulate in-vivo conditions, and analysed using the available linear solver. The von Mises stress distributions are generated for each of the cavity configurations and the maximum observed stress is compared with the maximum strength for the ceramic material used. It is clear that the flexural strength of the ceramic would not be the limiting factor that governs life span. Finally it is proposed that a more appropriate way to assess the life span may be to compute tensile strains (or stresses) that could propagate flaws as cracks from the cavity boundaries. Preliminary results from the manual post-processing of the FEA results indicate that this approach is feasible. For the examples presented in this paper, the single elliptical access cavity seems to be the preferred option and this would seem to be consistent with current clinical practice.

Section 6.6

Supplemental:

Finite Element Analysis of lithium disilicate glass-ceramic discs with representative endodontic access cavities

This additional work was not intended for publication but was carried out as an exploratory exercise.

6.6 FEA of LDGC discs with representative endodontic access cavities

6.6.1 Introduction

This section is the result of a collaboration with the Engineering Department, UCC. The aim of this work was to, compliment and supplement the *in vitro* EBFS testing of endodontically accessed and repaired lithium disilicate glass-ceramic (LDGC) disc samples reported in Chapter 4. The relevant material and geometric properties of the LDGC material were replicated in the computer model. The model was validated by performing manual calculations using the Timoshenko theory of simple plate bending (Timoshenko and Woinowsky-Krieger, 2010). FE models of discs were developed to investigate the effect on strength for different dimensions of endodontic access cavities and resin composite repair materials with different moduli of elasticity. Finite element analysis (FEA) can be used to analyse and solve complex biomechanical problems. The basis behind the software involves dividing the problem area into a number of smaller problem domains, which are much easier to solve. Once a model is created, any variable may be changed relatively easily in order to investigate the issue at hand.

The current work was unique in that FEA was used to analyse stress distributions, deflections and bending moments of repaired disc geometries in contact with a constant load, while changing key variables.

Figure 6.12 outlines the process used to develop the simple plate model on the FEA package STRAND7 (Strand7-R24, Pty Ltd., UK). The properties of the disc material were obtained. The material was considered to be an elastic isotropic material. Thin plates (15 mm by 1.4 mm) which were fabricated in the laboratory *in vitro* (see Chapter 4) were virtually modelled to produce a fully functional simply supported circular plate model. Simple central loading was initially applied to the prototype model and its accuracy was validated with manual calculations. The validated models were then loaded to simulate the concentric ring load applied in the laboratory. Plate deflection, bending moment and critical points were analysed.

6.6.2 Methods

Once verified, the prototype model was used to analyse various different plate variables and the response to applied loads. The analysis of five scenarios were selected to include the intact disc, two different access cavity dimensions and two different resin composite repair materials on the FE program (Table 6.2).

Group	Access cavity dimension (mm)	Modulus of elasticity of access cavity repair material (GPa)
1	Intact	Intact
2	3	5.3
3	3	14.1
4	4	5.3
5	4	14.1

Table 6.2. Description of 5 different variables which were modelled using FEA.

The load and support device employed in the laboratory was of concentric ring formation, this was replicated in the FEA program. The load ring was 6 mm in diameter and the support ring underneath the sample was 12 mm in diameter. While the diameter of the plate was 15 mm and the support was 12 mm, the overhanging 3 mm was deemed unnecessary in the FEA model therefore the plate was cutback to 12 mm. The overhanging material was given no special consideration for manual calculations of *in vitro* results as its effect is known to be negligible (Kelly, 1995). In order to make the modelling and solving process possible the following assumptions were made;

1) The plate material is elastic, homogenous and isotropic.
2) The plate is initially flat.
3) The plate thickness is roughly ten times smaller than the length.
4) That small deflections occur.
5) The middle surface has a small slope after deflection.

6) The lines initially normal to neutral surface remain normal after bending (Kelliher, 2010).
7) The normal stresses acting on the neutral surface are negligible.
8) The strains produced by in-plane forces are very small.

6.6.2.1 Modelling process

Using Auto-Cad, concentric circles were drawn with diameters starting at 12 mm and stepping in 1 mm each time. This file was then imported into the Strand7 file, which provided the outline of the model. A flow diagram presents a simplified outline of the process (Figure 6.12).

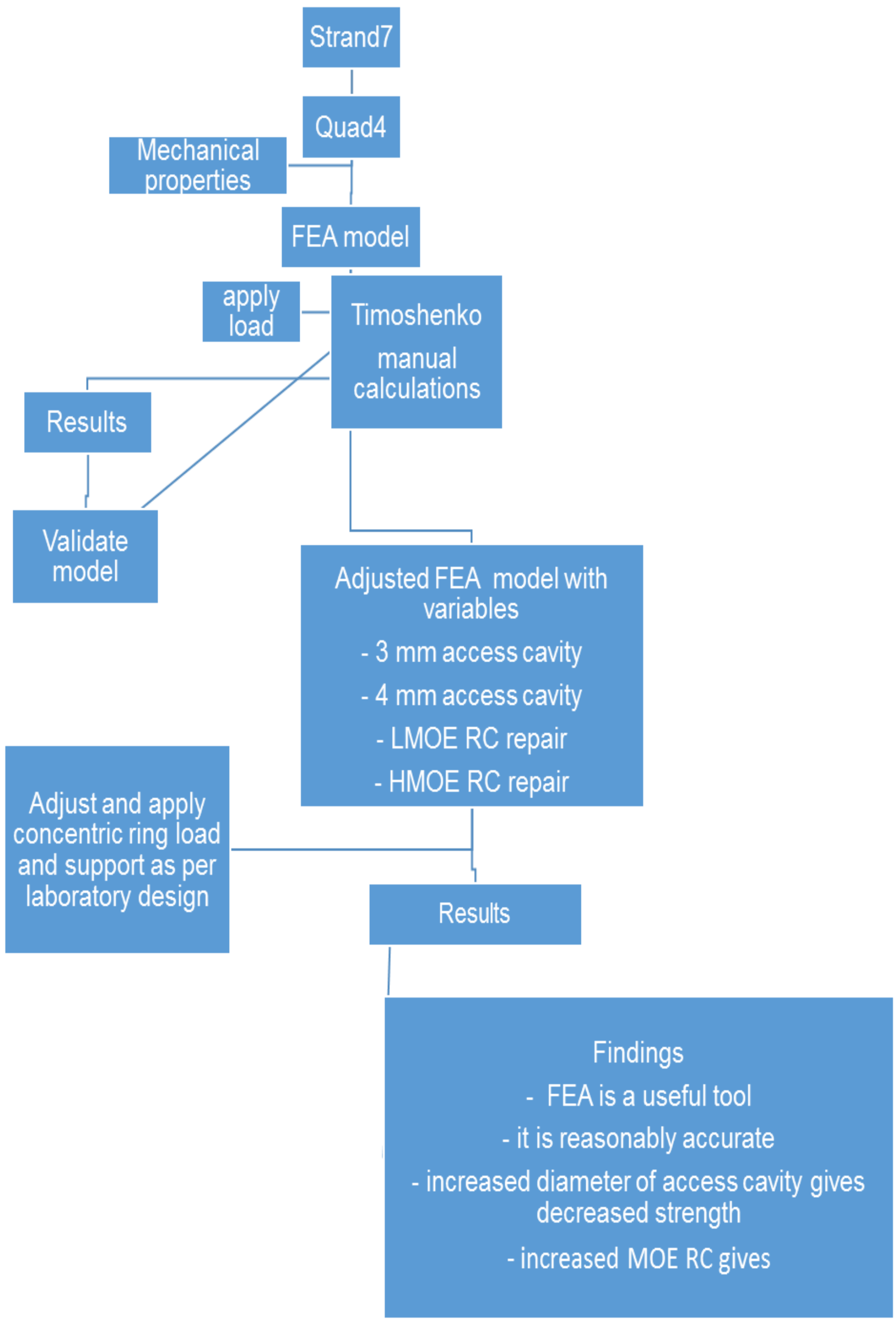


Figure 6.12. A flow diagram outlining a simplified overview of the FE modelling process used to build the disc shaped model and apply the different variables to it.

A detailed description of the choices made during the modelling process and also the reasons behind these choices is provided. All element descriptions and recommendations of modelling come from the STRAND7 (Strand7-R24, Pty Ltd., UK) help guide. The topics covered in this section include the,

1) Element type
2) Element geometry
3) Plate element type
4) Material model
5) Restraints applied to the boundary of the model.

6.6.2.2 Element type

The Strand7 element library includes both linear (low order) and quadratic (high order) spatial elements and each type is available as either a triangle or a quadrilateral. Due to the fine grading of the mesh it was deemed adequate to model using linear elements. The process of modelling curved surfaces using linear elements is briefly described.

The QUAD4 surface element was chosen for this model. QUAD4 plates have 4 nodes, one at each corner. They do not, however, strictly have to be square or rectangular shaped. The QUAD4 plate was chosen in this design for its simplicity. One stipulation is that QUAD4 plates should be restricted to thin plate/shell models. Generally a thin plate is one with a diameter to thickness ratio of greater than 10. However, due to the restraints from the support conditions of the loading device, the ratio of diameter to thickness in this model was slightly less than 10. The QUAD4 graph closely resembled the deflection values predicted by the manual Timoshenko calculations, in conclusion it was decided to proceed with the design using QUAD4 elements.

6.6.2.3 Element geometry

The plate aspect ratio is the ratio between the longest and shortest edge of a rectangle. The aspect ratio of a square is 1 while a rectangle has an aspect ratio of greater than 1. The Quad4 elements being used are accurate with an aspect ratio of up to 4. In the current model the biggest aspect ratio occurs in the plate shown (Figure 6.13).

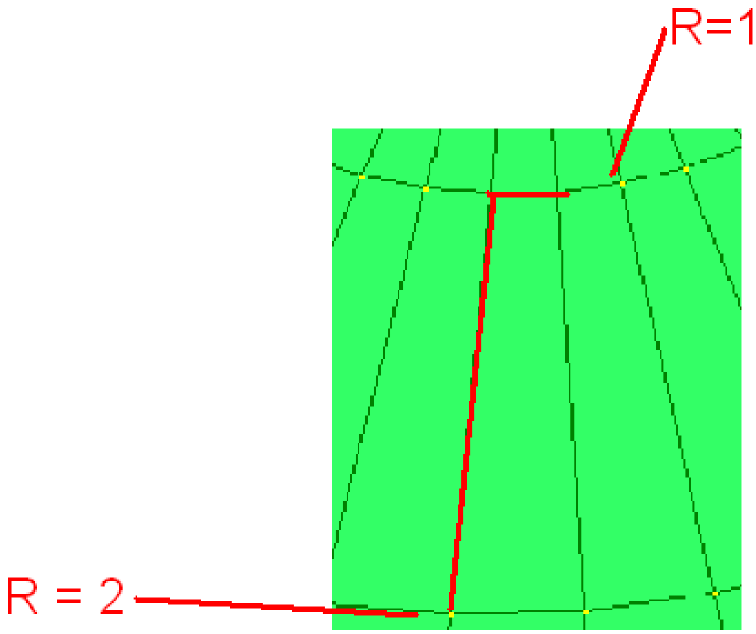


Figure 6.13. High aspect ratio (7) of QUAD4 surface elements.

6.6.2.4 Plate element type

The two dimensional surface elements may be used for the analysis of 2D planar structures, axisymmetric solids and 3D shell structures, however, in this project only the analysis of 3D shell structures hold any relevance. In order to replicate a 3D shell structure the surface element type chosen was plate/shell. For 3D analysis the surface elements carry membrane, in plane shear and bending loads. 3D elements are the only ones which allow out of plane displacements due to the moments applied. The alternative option to replicate the 3D shell structure was to use the 3D membrane; this plate element has no bending stiffness though and was neglected on this basis.

For the modelling of flat plates the recommended option by Strand7 is the ‘plate/shell’.

A complete disc structure (12 mm × 1.4 mm) of LDGC was successfully modelled (Figure 6.14 a)). The plate is used to model the mid-plane surface of the shell (Figure 6.14 b)), however, as the plate is a two dimensional element it has no physical thickness. Instead thickness is specified as material property.

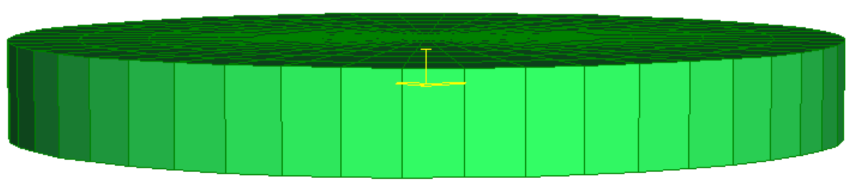


Figure 6.14 a) FE model of a complete disc structure of LDGC

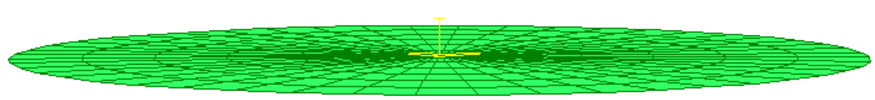


Figure 6.14 b) Mid-Plane Surface

6.6.2.5 Model material

It was appropriate to model the plate/shell element as an isotropic material. An isotropic material has uniform elastic moduli and strength in all directions. The 3 main material properties upon which the model is based are Young's modulus (E=9.5 MPa), Poisson's ratio (v= 0.234), and using these values the Shear modulus (G= 3.85 MPa) may be calculated from the equation, $G=E/2(1+v)$.

6.6.2.6 Restraints applied to the boundary of the model

Since the plate was modelled in 3 dimensions and not as an axisymmetric section, the Global Freedom conditions were set free in all directions. Boundary conditions are needed to solve the differential equations governing plate bending. In Strand7, nodal restraints are used to define these boundary conditions by either allowing or restricting displacement in a given direction for the chosen node. All nodes have six degrees of freedom; they can under-go both a translation and rotation in 3 directions. Freedom conditions always refer to the co-ordinate system in which they were originally defined. If the co-ordinate system in which the node was originally restrained is changed then the restraint value also changes.

6.6.3 Correlation with manual calculations

Before the project could proceed it was vital to lay down some sort of benchmark for the results. This benchmark will verify that the prototype model is performing accordingly and results match that of a simple hand-calculated example using the existing theory (Timoshenko and Woinowsky-Krieger, 2010).

The simple centrally loaded FE model was validated, both manual (Timoshenko equation) and computer (Strand7) approaches for calculating values of deflection, radial and angular moment showed close correlations. These are graphically displayed in Figures 6.15 and 6.16, respectively. The deflection and bending moment in a circular plate subjected to a point load at its centre were solved using two different approaches. Results from both approaches match up to a significant degree.

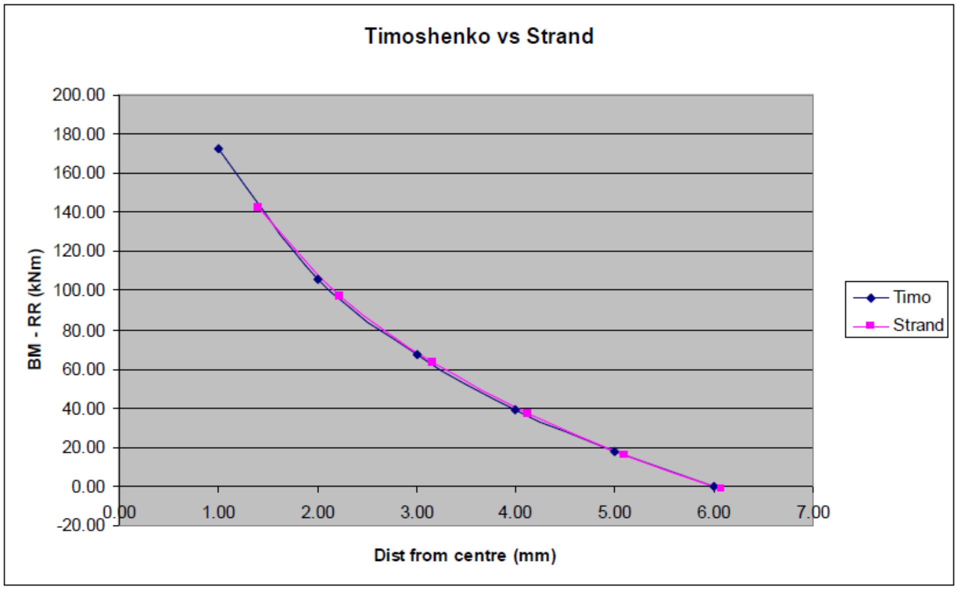


Figure 6.15. Graphic representation of plate deflection values obtained through Strand and Timoshenko methods. Both methods show excellent correlation with each other.

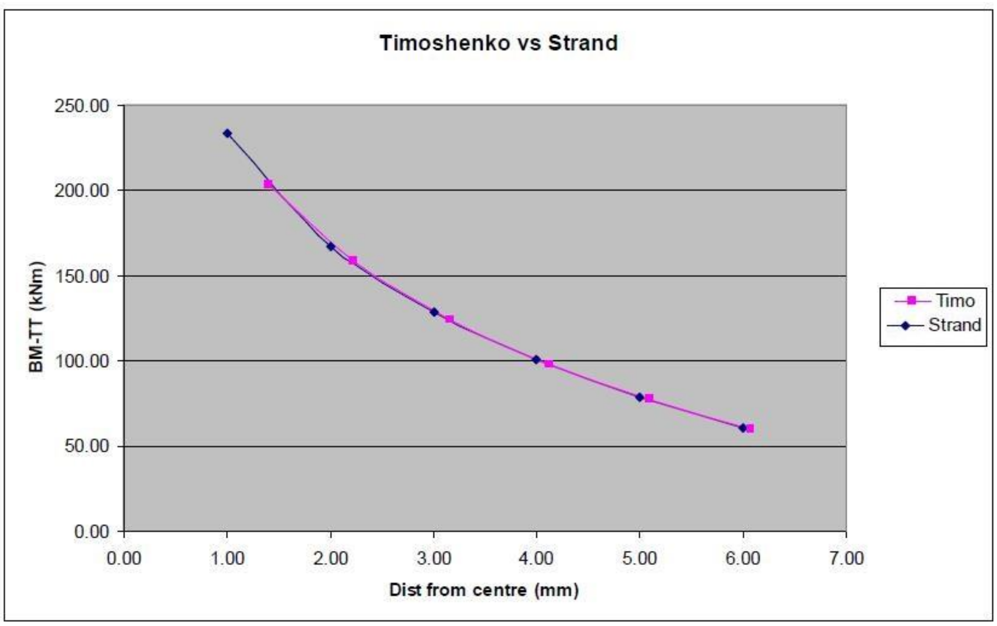


Figure 6.16. Graphic representation of plate bending moment values obtained through Strand and Timoshenko methods. Both methods show excellent correlation with each other.

Adjustments to the model which accounted for concentric ring load and support as per the *in vitro* scenario were thus applied to the validated FE model. The finite element was therefore validated and a further more detailed analysis was performed on five different models; one intact and four repaired (Table 6.2). The repaired samples varied in the size and stiffness of the repaired area. Each of these models was solved using Strand7. The results from each sample were graphed together and are compared under both deflection and bending moments. One of the goals of the project was to identify weak spots in the disc which could be potential starting points for failure in the material. The results section shall finish with these critical points in the discs being highlighted and discussed.

6.6.3.1 Further detailed analysis with extended variables

Each sample was analysed individually on Strand and the results were displayed using contour plots and vector diagrams. With mesh refinement and an increase in the number of nodes being used, analysing the vector diagrams became increasingly difficult and it was decided to just use the contour plots generated. In order to compare the 5 different models relatively quickly, a series of graphs across a diametric section of the plate were generated. Due to the symmetric nature of the plate, loading analysis of a diametric section was deemed representative of the entire plate (Figure 6.17 and 6.18).

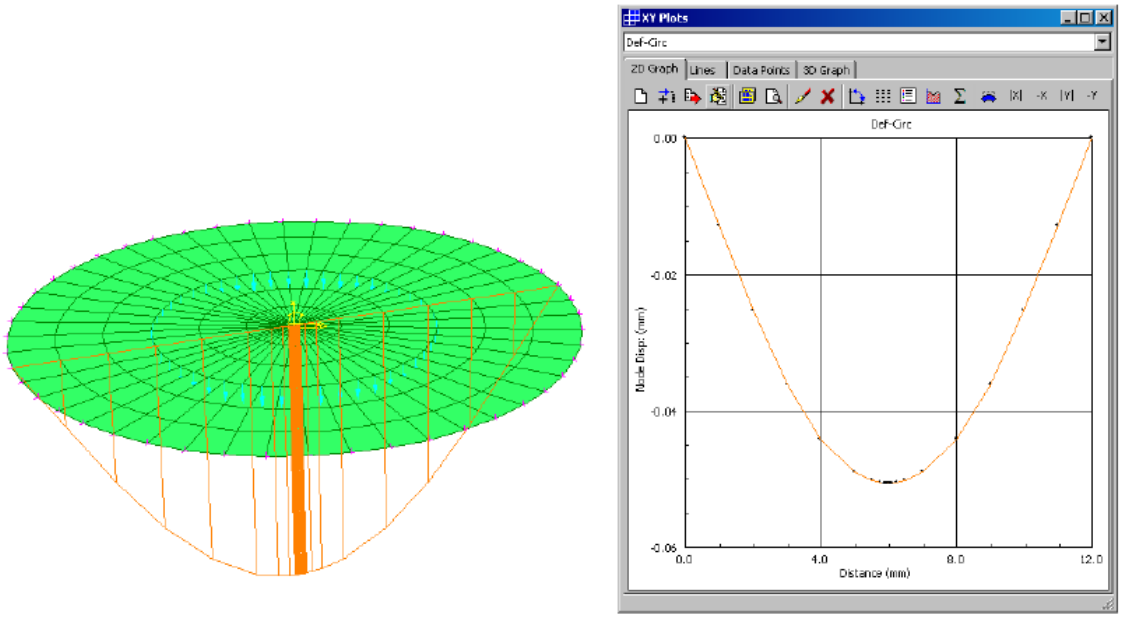


Figure 6.17. 3D graph of deflection of a diametric section deemed representative of the entire plate.

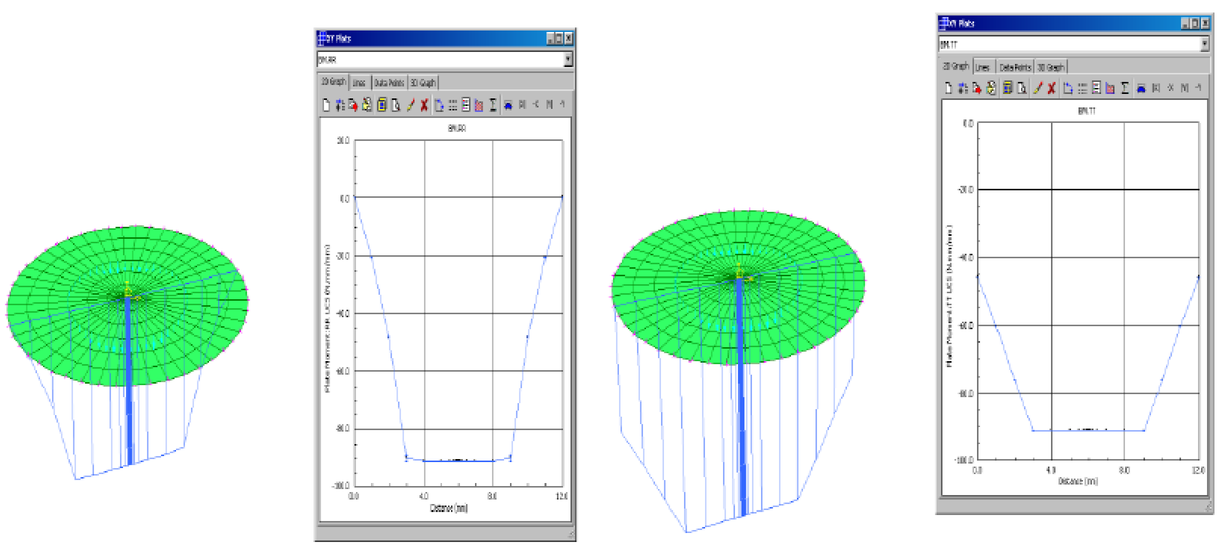


Figure 6.18. 3D graph of bending moments of a diametric section deemed representative of the entire plate.

6.6.3.2 Deflection

The results for each sample were then graphed together under the categories of displacement and moments. The variation in displacement (Table 6.3) between the samples is shown in Figure 6.19.

Group	Maximum deflection value (mm)	Load position
1	0.0506	Centre
2	0.074	Centre
3	0.069	Centre
4	0.0844	Centre
5	0.08	Centre

Table 6.3. Maximum deflection values for each of the 5 samples.

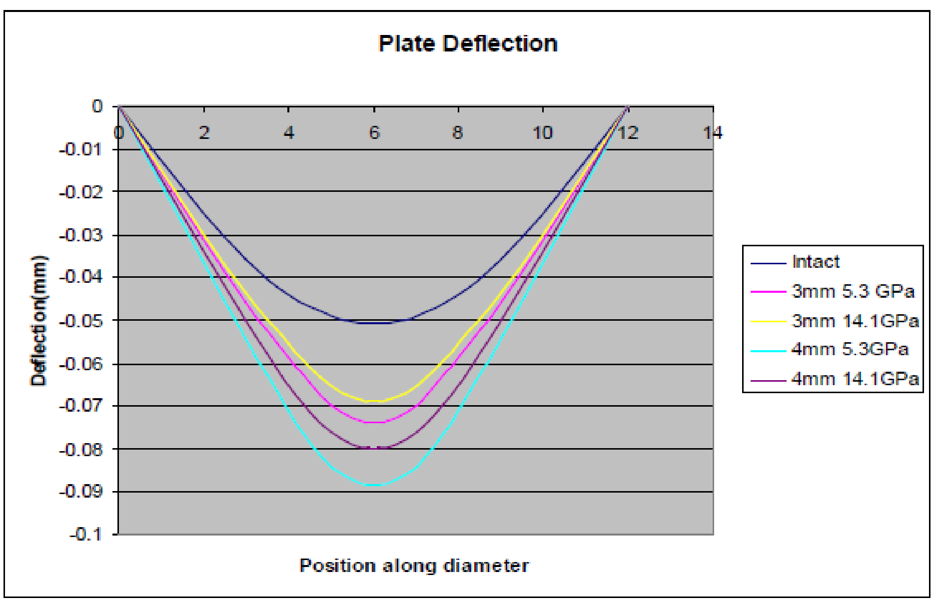


Figure 6.19. Deflection values for each sample as a result of loading a diametric section of each sample.

The graphs followed a predictable pattern, it can be seen that the intact disc which would intuitively be the strongest and deflects the least, whereas the disc with the greatest repaired area and least stiff repair material deflects the most.

It could be seen that for a 3 mm diameter access cavity filled with the higher modulus of elasticity resin composite (14.1 GPa) stiff material the maximum deflection was 0.069 mm. Increasing the repaired area had a more detrimental effect on the disc than replacing it with a less stiff material (increasing the deflection to 0.08 mm as opposed to 0.074 mm). The size of the repaired area was more important than the modulus of elasticity of the repair material.

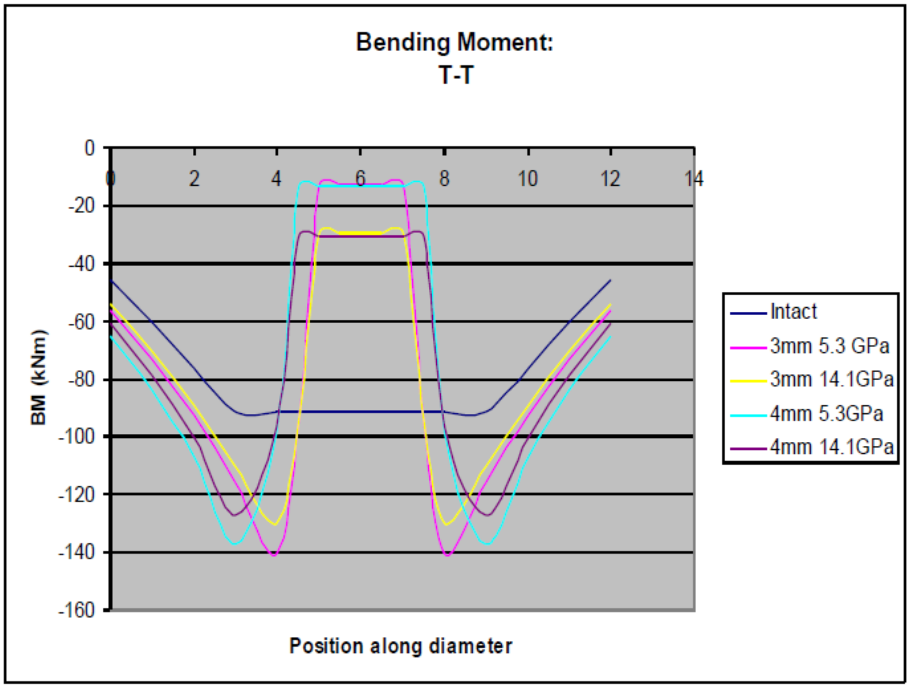


Figure 6.20. Moment diagrams depict a predictable pattern in the stiffer (14 GPa) repair material results in greater bending moment.

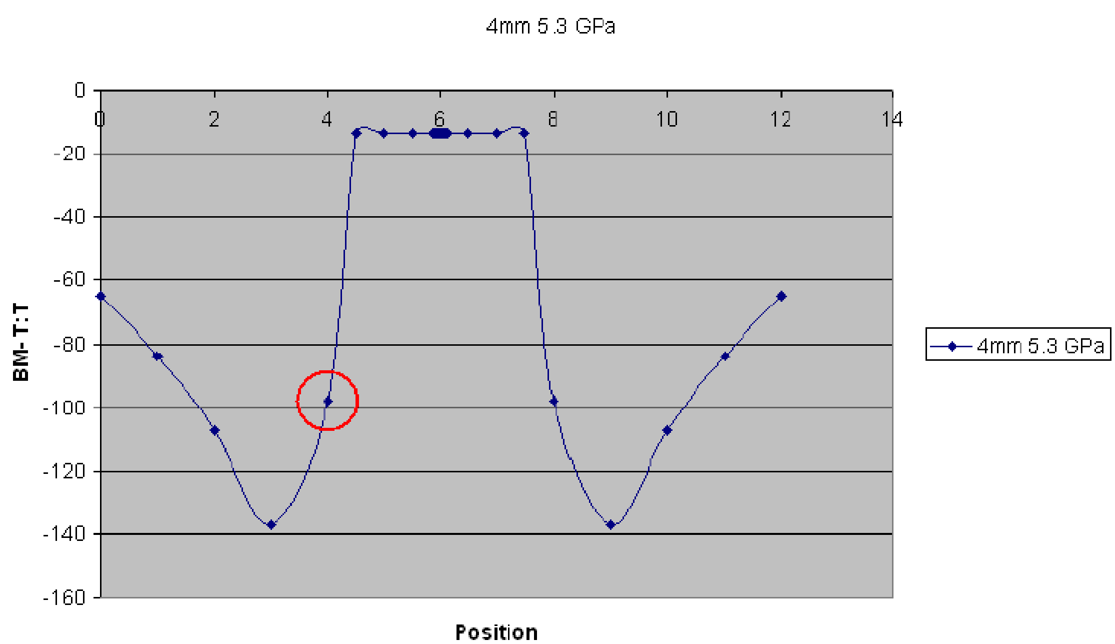


Figure 6.21. The bending moment at the red circle in sample 4 is 90 kNm greater than across the rest of the repair material, this indicates a critical point of weakness.

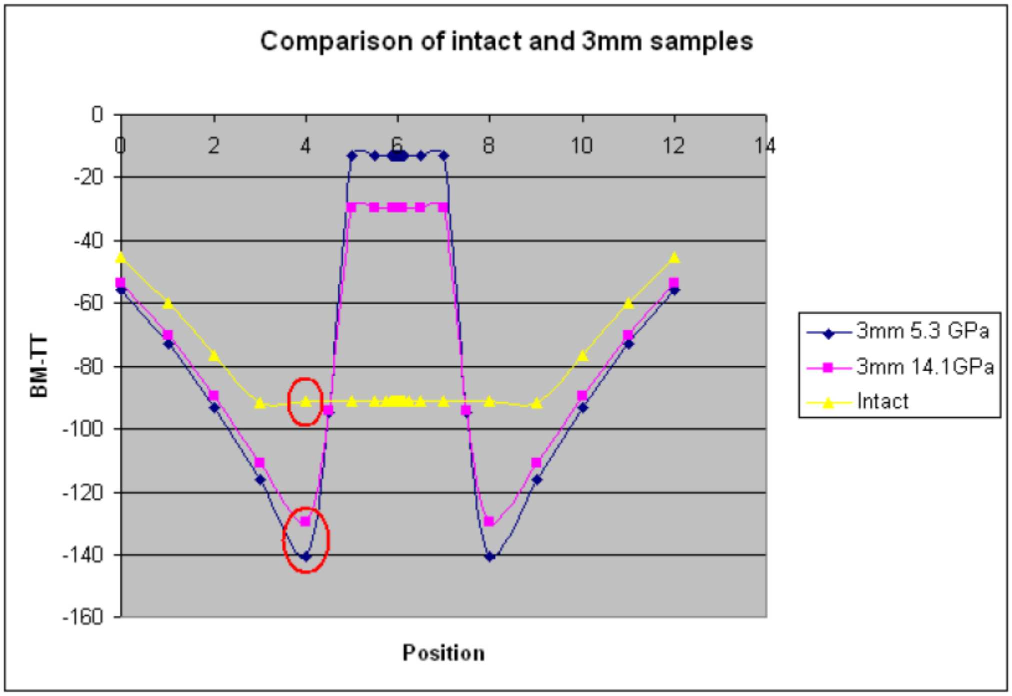


Figure 6.22. A greater bending moment is observed for 3 mm access cavities compared with the maximum value for the intact sample.

The moment diagram (Figure 6.20) also follow a predictable pattern, in the repaired discs, the stiffer material generally resulted in greater moment than the weaker material.

6.6.3.3 Critical points

The highlighted point in Figure 6.21 shows the material interchange in sample 4. The value of the bending moment at this point was nearly 90 kNm bigger here than across the rest of the weaker material. It was concluded that this point could be a point of weakness in the disc.

In the two samples with a 3 mm diameter it is seen that the bending moment increased beyond the point at which the load is applied to a value much larger than the max value for the intact sample (Figure 6.22). The max bending moment induced is between 40 – 50 kNm bigger in the repaired samples. This is also noted as a critical point in the 3 mm samples.

6.6.3.4 Correlation with *in vitro* laboratory results

The model was complex enough at this stage to replicate the discs used in the laboratory testing. The results taken from Strand7 were compared to the results from the lab. For an applied load of around 1000 N, the *in vitro* results yielded a displacement of about 1 mm (Figure 6.23). From Strand7 the maximum displacement in the intact disc was 0.056 mm (Table 6.3). This was a huge difference and initially considered unacceptable. It was at odds with the initial model which was benchmarked and deemed to be working to an appropriate degree. However, after some deliberation it was noted that the change in deflection between the intact and repaired discs was similar for both approaches. From Strand7 the deflection changes by about 25%. This is about the same from the laboratory samples (Figure 6.24).

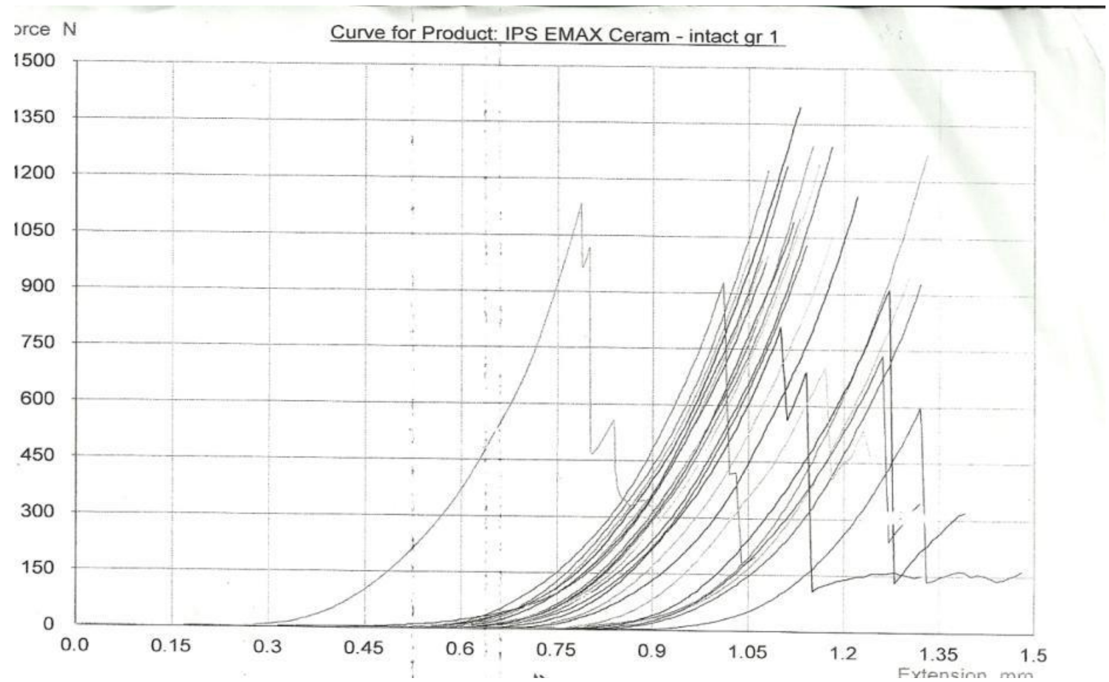


Figure 6.23. An approximately 1 mm displacement demonstrated when an approximately 1000N load is achieved for intact LDGC disc samples.

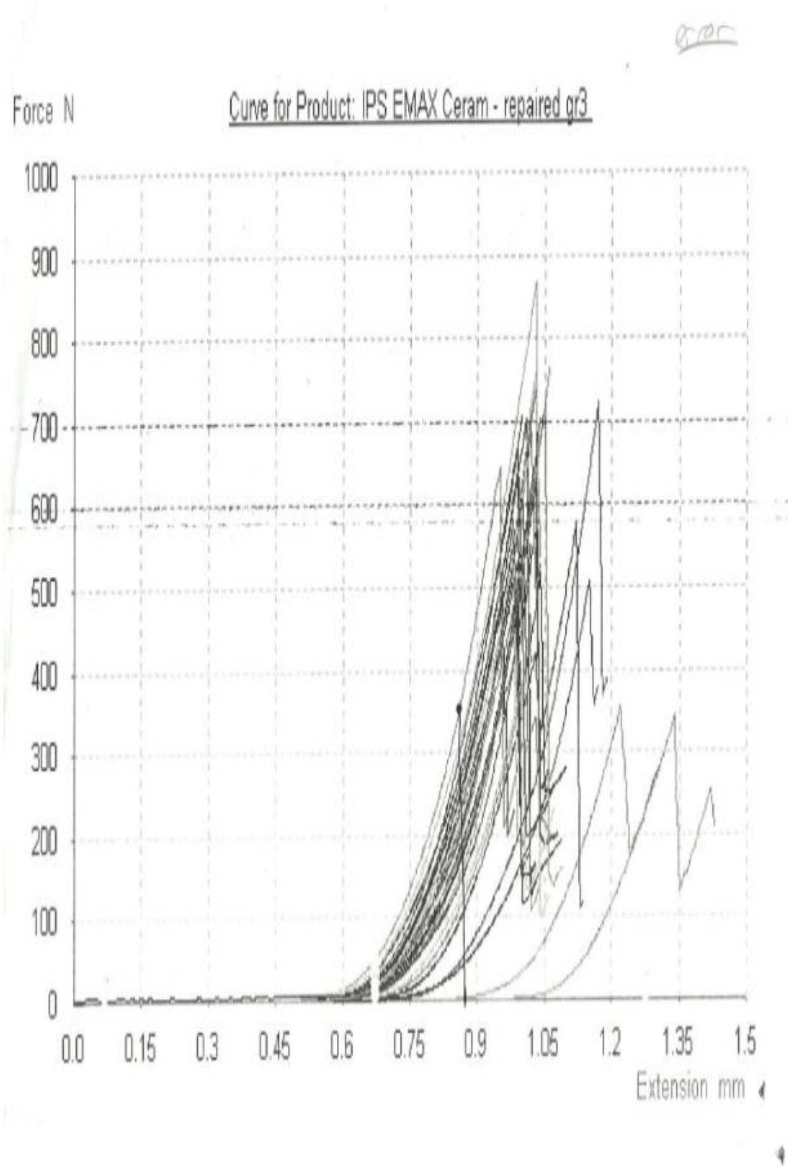


Figure 6.24. An approximately 25% deflection is demonstrated by loading LDGC discs with 3 mm access cavity repaired with resin composite.

An objective of the project was to be able to accurately map stress changes across the disc. It was concluded that the change in results between the intact and repaired sample was quite accurate and that the results themselves were out by a factor. This factor may either have arisen in the analysis of the disc or else the laboratory procedure.

6.6.4 Error

A number of inaccuracies are apparent from the results in this work. From studying the force versus displacement graph (Figure 6.24) of the laboratory testing it is clear that the material was exhibiting non-linear behaviour. However, for this project it was to be assumed that the material was an elastic-isotropic material. The question arises as to how the material becomes non-linear or how non-linear behaviour is triggered in the disc. Two sources have been identified as possible reasons for this. These are the material properties and the loading procedure of the disc respectively. Additionally, other small areas of possible error shall be discussed.

6.6.4.1 Sources of error

To create an accurate model it is advised that a non-linear analysis be carried out. Before this is undertaken, however, it is important to attempt to explain why the material is non-linear. More information would subsequently be needed on the material properties and loading procedures of the plates in the laboratory. Composites are man-made materials and therefore generally are not naturally isotropic, however material processing can influence this.

There may also be error induced during the loading sequence. Normally in general engineering and science experiments, dimensions are maximised in order to reduce the percentage error. Due to the extremely small nature of the sample, any error, no matter how tiny, may cause significant deviation in results. This could be anything from placing the specimen in slightly the wrong position to the specimens' surface not being completely flat and consequently the entire load ring not coming into contact with the sample at the same time. The behaviour of the sample during loading should also be investigated. If crack propagation occurs during loading then the structural integrity of the material may be severely compromised. Also the material may undergo crushing from the load ring. The behaviour of the samples during this procedure may provide useful information and could possibly be obtained by capturing the failure process on a high resolution camera. This affects the sample by initiating crack propagation. As well as this the ring may also embed into the material. This would then lead to a reduction in bending thickness of the sample. As discussed previously in the section on plate bending, the thickness of a plate has a large influence on flexural rigidity of the plate.

Further study of plate bending should also be taken, particularly the study of thick plates and plates with large deflection. It was a rigorous assumption in the methods that the plates only under-go a small deflection. The formulae used in the calculations in this project are based on this assumption (Timoshenko and Woinowsky-Krieger, 2010), the limit of which is about 25%. On this basis the deflection should be restricted to around 0.35 mm, however, it can be seen from the graph (Figure 6.23) that the deflection approaches values of 1 mm in some cases which is unacceptable. The solution to this would be to alter the dimensions of the load or support device or the thickness of the plate or embrace the study of thick plates. The loading device supports the disc at a diameter of 12 mm, thus from theory the thickness of the samples should be limited to 1.2 mm. However, the average thickness of the samples in the current study were 1.4 mm.

6.6.5 Conclusion

It was found that the size of the repaired area is more critical than the stiffness of the material used. However, bigger moments were induced in the 3 mm samples than their respective 4 mm counterparts with the biggest occurring in the 3 mm sample repaired using the weaker material. A compromise may have to be made between changing the material property and varying the size of the repaired hole in order to find the best solution. It is clear that the results are out by a factor. As a benchmark had been previously established, the model was deemed to be of adequate accuracy to analyse the more complicated discs as long as the assumptions made at the start of the project were held to. The assumptions may have been compromised during either the analysis process or during the laboratory tests. However, it must be noted that the finite element package is useful and reasonably accurate at graphing the changes in both deflection and moment between the samples.

Reasons for discrepancies in the results could be down to either an error in the analysis or else in the lab procedure. From re-examination of the force-displacement graph it was found that the material in the lab is displaying non-linear behaviour. The non-linearity of the material is one reason to explain the factor of error. A non-linear material is a much more complex problem than we had first anticipated and will require a non-linear analysis. While models were analysed as elastic in this project which does not perhaps represent the material in the truest sense, some interesting results were still obtained. The finite element method significantly reduced time in the analysis of plate elements when compared to the Timoshenko calculations at the preliminary point of the modelling process. Results from various samples were quickly compared and a quicker analysis time was desirable. The variation in results between the intact and repaired samples at least followed the intuitive path with the repaired discs having much less resistance to deflection. Also preliminary critical points in the disc were identified. These occurred generally at the interchange between materials. The finite element package was also able to clearly show the extra moment taken in the 3 mm repaired samples.

This current study was supplemental to the in vitro testing in Chapter 4. It employed a novel and effective approach for the investigation of FEA modelling of endodontic access cavities in representative LDGC disc samples. It has provided an innovative starting point to this issue where further research could be explored.

Chapter 7

Summary

7.1 Summary

This research had the following objectives:

1. To review the existing literature in relation to endodontically accessed all-ceramic crowns.
2. To investigate the influence of simulated endodontic access cavity size and the modulus of elasticity of resin composite repair material on the mean equibiaxial flexural strength of representative lithium disilicate glass-ceramic (IPS e.max® Press) disc substrates *in vitro*.
3. To determine whether the geometry of the access cavity and its repair influence the mean failure load of endodontically accessed lithium disilicate glass-ceramic (IPS e.max® Press) crowns *in vitro*.
4. To construct and explore computer simulated geometric models of a lithium disilicate glass-ceramic (IPS e.max® Press) crown.
5. To virtually model selected endodontic access cavity geometries in a LDGC crown. To apply a virtual loading scenario and conduct a stress analysis using Finite Element Analysis.

The findings of the thesis will be summarised according to each of the above objectives.

1. To review the existing literature in relation to endodontically accessed all-ceramic crowns.

A systematic search of the existing literature in the subject area was undertaken, using selected Medical Subject Heading's for appropriate electronic databases. Two focus questions were developed and refined, and thus the systematic review was developed in an attempt to address these questions. The systematic review highlighted the lack of research which the topic has attracted to date. Some potentially influential factors that may contribute to the mechanical properties of endodontically accessed all-ceramic crowns were synthesised from the articles included in the systematic review, this was the subject matter in Chapter Three. The full text articles, which were excluded from the search at the second round exclusion level provided additional information in the subject area and facilitated a thorough review of the general literature in Chapter Two, Section 2.5 of this thesis, and addressed the first objective of the study. These articles also assisted in formulating ideas for proposed future research applicable to all-ceramic crowns.

2. To investigate the influence of simulated endodontic access cavity size and the modulus of elasticity of resin composite repair material on the mean equibiaxial flexural strength of representative lithium disilicate glass-ceramic (IPS e.max® Press) disc substrates in vitro.

The second objective of the thesis was addressed in Chapter Four. Simple disc substrates of LDGC were employed to; investigate the effect of access cavity dimension and the moduli of elasticity of resin composite repair material, on the EBFS. The EBFS was significantly reduced with the introduction of an access cavity. The EBFS was further reduced when the dimension of the access cavity was increased from 3 mm to 5 mm in diameter. Repair of the access cavity with a resin composite did not result in an increase in EBFS. Increasing the MOE of the repair resin composite was not concomitant with increasing the flexural strength of the LDGC material. While a significant decrease in strength was apparent after preparation of an endodontic access cavity, the values obtained were comparable to those of some intact, but weaker commercially alternative materials in the same category and restorations may therefore continue to serve in a definitive capacity.

In order to validate the repair protocol used in this chapter with those reported in the literature, a short study, which measured the mean shear bond strength (SBS) of resin composite to LDGC material, was carried out additionally and is reported in the Appendices. It was concluded that the values obtained were within the range of those reported in the literature.

3. To determine whether the geometry of the access cavity and its repair influence the mean failure load of endodontically accessed lithium disilicate glass-ceramic (IPS e.max® Press) crowns in vitro.

The third objective of the thesis is the subject matter of Chapter Five. The mandibular first molar is the most frequent tooth to receive endodontic treatment, it was chosen to model the effect on failure load of two geometries of endodontic access cavities in a LDGC material. A rhomboidal and rectangular access cavity was chosen to reflect the presence of either 3- root or 4- root canals as per the clinical scenario. Previous literature has claimed that repairing an access cavity in an all-ceramic crown can restore the failure load to that of the intact crown. However, it has been pointed out that since the crowns with an unrestored access cavity were not tested, that this assumption has not been validated. The findings indicate that the mean failure load of a LDGC crown with an unrestored rhomboidal access cavity was not significantly different from both that of the intact crown and those repaired with a resin composite material. However, for the rectangular access cavity, which is less common but necessary when a 4-canal root was present or as a result of overzealous access cavity preparation, the mean failure load significantly decreased compared with the intact crown, but was restored to the value of the intact crown when a resin composite repair was carried out.

4. *To construct and explore computer simulated geometric models of a lithium disilicate glass-ceramic (IPS e.max® Press) crown.*

A mandibular first molar tooth was scanned by a Scanco® CT40 µCT device and the outputted data was saved in the scanner's native format. A parametric model was developed using a non-uniform B-spline (NURBS) based solid geometric model. The necessary material properties were inputted and the virtual model was successfully generated using a finite element approach. The fourth objective was thus achieved.

5. *To virtually model selected endodontic access cavity geometries in a LDGC crown. To apply a virtual loading scenario and conduct a stress analysis using Finite Element Analysis.*

Endodontic access cavities in LDGC crowns were modelled using a Finite Element (FE) method, which was the first study in the dental literature which employed FE for this purpose. Three variations in the access cavity dimensions were modelled in a mandibular first molar LDGC (IPS e.max® Press) crown, an *in vivo* loading scenario was applied and the stress was analysed using FEA. In conclusion, recommendations were made which indicate that high curvature access cavity walls should be avoided, since stress concentration was maximum for this design as opposed to elliptical or double access cavity designs. This was the fifth and final objective of the thesis and is the subject matter in Chapter Six. In addition (Section 6.6), FE modelling of representative LDGC disc specimens with two access cavity diameters and two resin composite materials with different moduli of elasticity was successfully undertaken. This work complimented the EBFS of LDGC discs which is the content of Chapter 4. It concluded that the size of the access cavity was more critical than the material which it was repaired with.

7.2 Suggestions for further research

The effects of endodontic access cavity preparation in all-ceramic crowns *in vitro* has hitherto fore been a relatively unexplored topic and continues to provide a fertile area for future research activity.

- The systematic review highlighted that clinical studies were conspicuously lacking in the literature on this topic which would inform the survival probabilities of teeth which had been provided with an all-ceramic crown and subsequently received endodontic treatment via crown perforation *in situ*. In order to inform clinical survival statistics, randomised controlled trials, retrospective and prospective studies would provide valuable information.

- Variations in the protocol for the repair of endodontic access cavities in all-ceramic crowns and representative disc substrates and the effect on strength should be investigated. Close fitting ceramic inlays as an alternative to resin composite repair may offer a superior ‘repair’, in terms of strength, aesthetics and wear as close as possible to that of the intact crown. The effect of different categories of luting agents in relation to strength and reliability could be modelled in disc substrates and the effect on the strength of LDGC determined. The response of other popular all-ceramic materials such as, CAD/CAM manufactured LDGC and Zirconia as, endodontic access repair materials repair, on strength should be investigated. ‘Real-time’ failure observations of fracture events may also yield additional information. Laboratory studies to investigate the long-term survival of restored restorations should be performed, therefore the effects of dynamic and cyclic loading in the presence of moisture could be analysed.

- In this study, the successful and novel use of FEA was applied to virtual models of all-ceramic crowns with endodontic access cavities was demonstrated. The use of FEA could be further employed in crown specimens to model the response of various tooth types and the different forces which they are subjected to depending on their location in the oral cavity. FEA could also be further utilised with crowns and representative disc specimens to explore various potentially influencing factors including different;

- ceramic materials
- access cavity geometries
- loading configurations
- luting cements
- access cavity repair materials

- The optimum repair protocol with respect to the resistance of coronal microleakage should be determined for different all-ceramic crown materials. This combined with the effects of thermocycling and dynamic loading on microleakage, would provide usual information to inform clinical protocols.

- The effect of endodontic access preparation on crown retention was investigated by few authors in the literature and only in respect to metal-ceramic crowns. While it would be difficult to design a study to investigate this problem, given the brittle nature of ceramics, it should be possible especially for high strength polycrystalline ceramic crowns. Of particular concern would be the retention of ceramic crowns which had an endodontic access cavity prepared and/or restored but had not been adhesively bonded or had questionable resin-ceramic bonding ability.

Chapter 8

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Chapter 9

Appendices

9.1 Publications

DENTAL MATERIALS 29 (2013) 626–634

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dental materials

Endodontic access cavity simulation in ceramic dental crowns

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ABSTRACT

Objectives. It is proposed that a non-uniform rational B-spline (NURBS) based solid geometric model of a ceramic crown would be a flexible and quick approach to virtually simulate root canal access cavities. The computation of strain components orthogonal to surface flaws generated during the drilling would be an appropriate way of comparing different access cavity configurations.

Methods. A μCT scan is used to develop a full 3D NURBS geometric solid model of a ceramic crown. Three different access cavity configurations are created virtually in the geometric model and there are then imported into proprietary finite element software. A linear analysis of the each crown is carried out under appropriate in vivo loading and the results are post-processed to carry out a quantitative comparison of the three configurations

Results. The geometric model is shown to be a flexible and quick way of simulation access cavities. Preliminary indications are that post processed strain results from the finite element analysis are good comparators of competing access cavity configurations.

Significance. The generation of geometric solid models of dental crowns from μCT scans is a flexible and efficient methodology to simulate a number of access cavity configurations. Furthermore, advanced post-processing of the primary finite element analysis results is worthwhile as preliminary results indicate that improved quantitative comparisons between different access cavity configurations are possible.

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1. Introduction

Classical structural mechanics fails to produce an adequate elucidation of the stresses and strains developed in a system as geometrically complex as a grinding tooth. Naturally, the boundary of such a surface cannot be described by a singular component such as a beam or a plate, and therefore a computer simulation must be carried out. All physical phenomena are modeled mathematically as partial differential equations. It is rare that the solutions for these partial differential equations are trivial [1], but since the development of the computer, numerical solutions are now mainstream. For boundary value field problems, including structural mechanics, the finite element method (FEM) is the standard numerical approach. The ability of the FEM to accurately compute stress

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Review article

The effect of endodontic access on all-ceramic crowns: A systematic review of *in vitro* studies

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ABSTRACT

Objectives: The aim of this systematic review was to identify from *in vitro* studies the effect of endodontic access on the fracture resistance and damage around the access cavity of all-ceramic crowns.
Data: The articles identified were screened by two reviewers according to inclusion and exclusion criteria. The reference lists of articles advanced to second round screening were hand searched to identify additional potential articles. The risk of bias for the articles was independently performed by two reviewers.
Sources: An electronic search was conducted on PubMed/Medline, Web of Science, Scopus and Embase databases with no limitations.
Study selection: 383 articles were identified, of which, eight met the inclusion criteria and formed the basis of this systematic review. Factors investigated in the selected articles included the, presence of microcracks at the access cavity, repair protocol, ceramic type, crown fabrication method, luting agent and grit size of the diamond bur. The risk of bias was deemed to be high for three, medium for two and low for three of the reviewed studies. The high level of heterogeneity across the studies precluded meta-analyses.
Conclusion: Based on the currently available scientific evidence, a 'best practice' protocol with regard to improving the fracture resistance of endodontically accessed and repaired all-ceramic crowns cannot be conclusively identified. However, some key factors which potentially impact on the fracture resistance of endodontically accessed and repaired all-ceramic crowns have been isolated. Cautious clinical interpretation of these factors is concluded for the maintenance of the crown as a permanent restoration.
Clinical significance: Key factors which impact on the fracture resistance of endodontically accessed and repaired all-ceramic crowns have been isolated from *in vitro* studies. Cautious clinical interpretation of these factors is advised for the maintenance of the crown as a permanent restoration.
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1. Introduction

The provision of dental crowns represents a sizeable proportion of treatment units provided to patients presenting to the General Dental Services (GDS) in England and Wales with over 1.1 million dental crowns placed annually [1]. Additionally, dental crowns are frequently the treatment modality of choice for US dentists with approximately one crown being provided to every 2.3 US adult patients in 2012 [2]. The increased incidences of patient treatment with dental crowns in general dental practice [3] is often in preference to less destructive options including bleaching, resin composite (RC) restorations or minor orthodontic treatment [2,3]. Dental crowns are perceived to be a durable and uncomplicated option whilst simultaneously generating the highest income [2]. However, crown preparation is irreversibly destructive to tooth tissue, typically 62–73% of tooth structure is removed during preparation for anterior all-ceramic crowns [4]. The link between tooth destruction and possible pulpal complications is well documented in the dental literature [4–10].

Goodacre et al. [11] reviewed the literature to investigate the incidence of clinical complications of dental crowns over a 50-year period. The authors combined the results of five studies [7,12–15] and identified that 3% (27 of 823) of dental crowns required subsequent endodontic treatment. A 2.1% incidence of loss of

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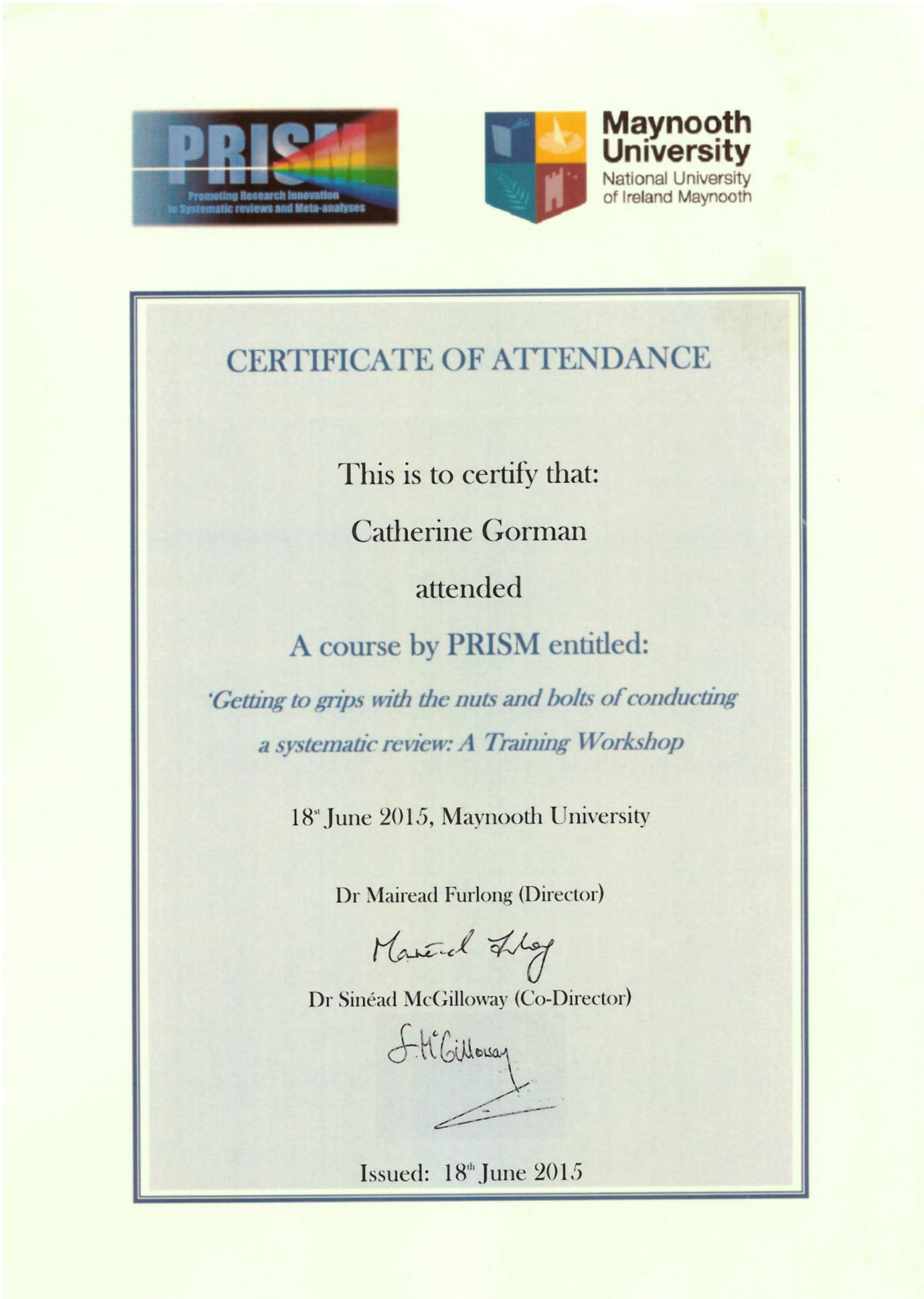
9.2 PRISM - Systematic review training workshop


PRISM
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CERTIFICATE OF ATTENDANCE

This is to certify that:

Catherine Gorman

attended

A course by PRISM entitled:

'Getting to grips with the nuts and bolts of conducting a systematic review: A Training Workshop

18st June 2015, Maynooth University

Dr Mairead Furlong (Director)

Dr Sinéad McGilloway (Co-Director)

Issued: 18th June 2015

9.3 PG 6001 (5 credit UCC module) Scientific Training for Enhanced Postgraduate Studies (STEPS)

Gorman, Catherine

From:	Kelly, Alan
Sent:	19 August 2010 10:56
To:	Gorman, Catherine
Subject:	STEPS (PG6001)

Dear Catherine,

Many thanks once again for your participation in the module PG6001 in April. I am writing to confirm that you have successfully completed all required elements of the module, and hence I will now inform the UCC Examinations Office to record 5 credits as passed on your academic transcript.

In terms of the PowerPoint presentation you submitted for assessment, it was very good, with nice use of images and schematics.

May I take this opportunity to wish you all the best in your future research.

Best wishes,

Alan Kelly

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Dean of Graduate Studies and
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University College Cork, Cork, Ireland
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9.4 Result of Equibiaxial flexural strength pilot study for LDGC disc substrates with a 2.5 mm representative endodontic access cavity

This work was performed as a pilot test to inform the materials and methods which would be employed in Chapter Four. The same protocols used in Section 4.2 were employed here with the exception of the access cavity diameter, which was 2.5 mm in this pilot study.

The results are included for information only. Thirty (n=30) specimens were tested. A mean flexural strength of 151.4 ± 26.8 MPa was determined for this group. The coefficient of variance was calculated to be 17.7 %. The mean internal access cavity diameter was 2.42 ± 0.08 mm with a coefficient of variance of 3.2 %.

The access cavity diameters for the final study were consequently determined to be more clinically appropriate and have sufficient differences relevant to the test apparatus used, for 3 mm and 5 mm representative endodontic access cavities.

9.5 Shear bond strength (SBS) of resin composite to lithium disilicate glass-ceramic

Abstract

Objective: To validate the shear bond strength (SBS) between resin composite and a glass ceramic restorative material as a protocol for the resin composite repair of simulated endodontic access cavities in representative lithium disilicate disc specimens.

Method: Thirty lithium disilicate glass-ceramic (IPS e.max® Press, Ivoclar Vivadent, Schaan, Liechtenstein) specimens were ground flat with 180 grit SiC paper. The specimens were primed with 37% phosphoric acid/silane for 60 seconds. A cylindrical (3.35 mm diameter) resin composite button was light cured (Bencor Multi-T, Danville Engineering Co., Danville, CA, USA), to the primed glass ceramic surface for 40 seconds. The specimens were stored at room temperature (20 ± 2 °C) for seven days before testing. The ceramic-resin bond was subjected to a shear load at 0.75 ± 0.2 mm/min until failure. The fragments were collected and visually analysed to determine the mode of failure. The mean failure load, SBS and standard deviations were calculated for the data.

Results: The mean failure load (standard deviation) was 137.9 (51.4) N. The mean SBS (standard deviation) was 15.7 (5.8) MPa. The mode of failure was classified as adhesive, for 100% of specimens.

Conclusion: The mean SBS obtained in the current investigation is within the range of those reported in the dental literature.

9.5.1 Aim

The aim of this section was to ascertain and validate within the limitations, a mean value for the shear bond strength (SBS) of resin composite to lithium disilicate glass-ceramic (LDGC) materials which were intended to be used to repair the access cavities in disc specimens in Section 4.2.

9.5.2 Materials and Methods

The superfluous material from heat-pressing lithium disilicate glass-ceramic (LDGC) (IPS e.max® Press, Ivoclar Vivadent, Schaan, Liechenstein) disc specimens as described in Section 4.2 were recovered. Each specimen was cured in a cold mounting resin material (Vari-Set, 110028, MetPrep, Coventry, UK) and ground flat using 180 grit SiC paper (Buehler-Met, Lake Bluff, Illinois, USA). The materials and composition used in this study are presented in Table 9.1.

Material	Brand name	Composition	Manufacturer
Acid etch	Total etch	37% phosphoric acid	Ivoclar Vivadent, Schaan, Liechtenstein
Silane Bonding Agent	Monobond S	Adhesive monomers 4 (wt %) Ethanol 96 (wt %)	Ivoclar Vivadent, Schaan, Liechtenstein
Resin composite	Tetric EvoCeram	Bis-GMA, Urethane dimethacrylate, Ethoxylated Bis-EMA (16.8 wt %) Barium glass filler, Ytterbiumtrifluoride, Mixed oxide (48.5 wt %) Prepolymers (34.0 wt %)	Ivoclar Vivadent, Schaan, Liechtenstein
Lithium disilicate glass-ceramic	IPS emax® Press	70% Lithium disilicate crystals	Ivoclar Vivadent, Schaan, Liechtenstein

Table 9.1. Materials used in this study.

The LDGC specimens were cleaned to remove debris using a steam cleaner (Electronic steamer II, Amann Girrbach, 6842 Kobiach, Austria) and air dried. The surface of the specimens were treated with 37% phosphoric acid primer (Total Etch, Ivoclar Vivadent AG, Schaan/Liechtenstein) for 60 seconds, rinsed with water and dried with a stream of oil free air. The manufacturer's instructions for bonding resin composite were followed. A porcelain silane primer (Monobond S primer, Ivoclar Vivadent AG, Schaan/Liechtenstein) was applied to the ceramic for 60 seconds, after which any excess was dried with a stream of oil free air. A cylindrical stainless steel mould 3.35 mm in diameter (Bencor Multi-T, Danville Engineering Co., Danville, CA, USA), was placed in the centre of the specimen and was immediately filled with resin composite material (Tetric EvoCeram, Ivoclar Vivadent AG, Schaan/Liechtenstein) (Figure 9.1). A light curing device (Deguluv soft start, Dentsply, UK, nominal irradiance = 800 $mWcm^2$) was calibrated using a light curing meter (Henry Schein, Gillingham ME8 OSB, UK), then used to polymerise the resin composite for 40 seconds The mould was removed to yield a 3.35 mm diameter resin composite cylindrical button bonded to the glass-ceramic surface. The specimens were stored dry (20 ± 2 °C) for seven days until ready for shear testing.

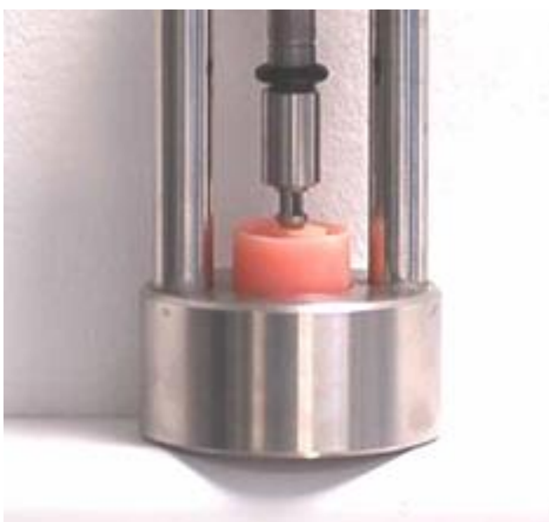

Figure 9.1. Cylindrical stainless steel mould (3.35 mm diameter) placed in the centre of the lithium disilicate specimen and filled with resin composite material (Tetric EvoCeram, Ivoclar Vivadent AG, Schaan/Liechtenstein). The resin composite was light cured for 40 seconds.

Each specimen was clamped in the guillotine of a Bencor Multi-T testing device (Danville Engineering Co., Danville, CA, USA) (Figure 9.1). A force was applied to the resin composite/ceramic interface using a tensometer (Tinius Olsen H10KS, Tinius Olsen Ltd, Perrywood Business Park, Redhill, Surrey, UK) at a crosshead speed of 0.75 ± 0.2 mm/min until the material failed (Figure 9.2). A 10 kN load-cell was used with a load range of 50%. The load at failure was recorded for each specimen and fragments retained for inspection.

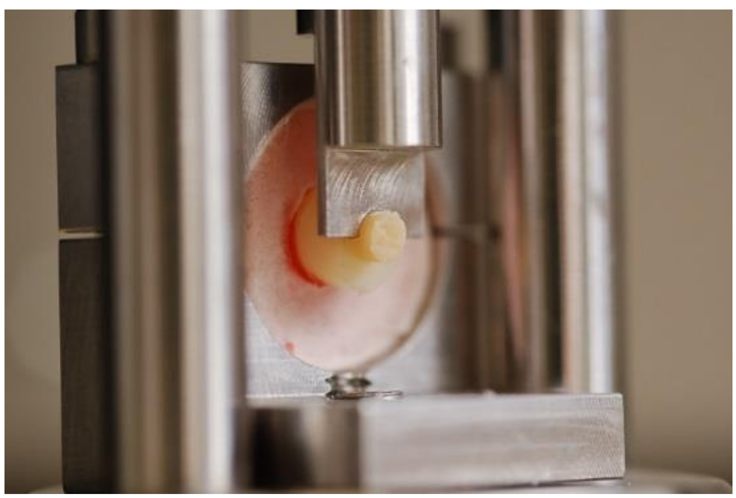

Figure 9.2. Shear bond (SBS) test for resin composite (Tetric EvoCeram) adhesively bonded to lithium disilicate glass-ceramic substrate (IPS emax® Press).

The interfacial SBS (MPa) was calculated by dividing the maximum failure load (N), by the circular bonding area A (πr^2) in mm^2. The fragments were examined visually to determine the mode of failure (adhesive, cohesive or mixed). A representative specimen was viewed with SEM (Zeiss Supra™

35VP). Summary statistical analysis were performed for the data to obtain mean, median, standard deviation, population mean (Standard Error of the Mean) and coefficient of variance.

9.5.3 Results

Value	**Measurement**
n	30
Mean load at failure (N)	137.9 (51.4)
Mean SBS (MPa)	15.5 (5.8)
Median SBS (MPa)	14.66
Standard Error of the Mean	1.066113
CV	37%

Table 9.2. Number of specimens (n) tested, mean failure load (N), mean and median shear bond strengths (SBS) in MPa, standard error of the mean and Coefficient of Variation (CV) for the data.

The results of the statistical analysis are presented in Table 9.2 and a boxplot summary in Figure 9.3. Thirty specimens were tested (n=30) and failure load values obtained for all specimens as no pre-test failures occurred. The mean load at failure and standard deviation was determined to be 137.9 (51.4) MPa. The mean SBS and standard deviation was 15.5 (5.8) MPa, the standard error of the mean was calculated to be 1.066 and the coefficient of variance was 37%.

Visual examination of the lithium disilicate glass-ceramic surfaces revealed that the mode of failure was adhesive for 100% of the specimens. An SEM image at high magnification (×300) of the glass-ceramic surface shows a scratched surface with grooves aligned to the polishing direction (Figure 9.4). An SEM image (×300) of the debonded surface of the resin composite reflects adaptation of the resin to the grooved surface. Voids (approx. 1 – 30 µm) are evident on the surface of the resin composite (Figure 9.5).

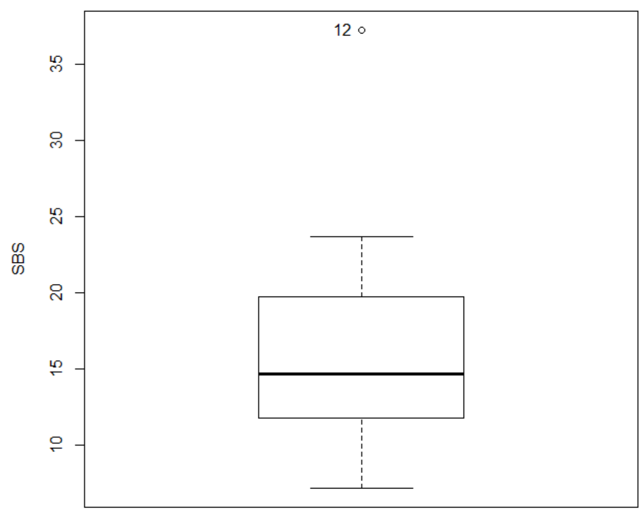

Figure 9.3. Boxplot summary including median, interquartile range and standard deviation for the SBS dataset (n=30).

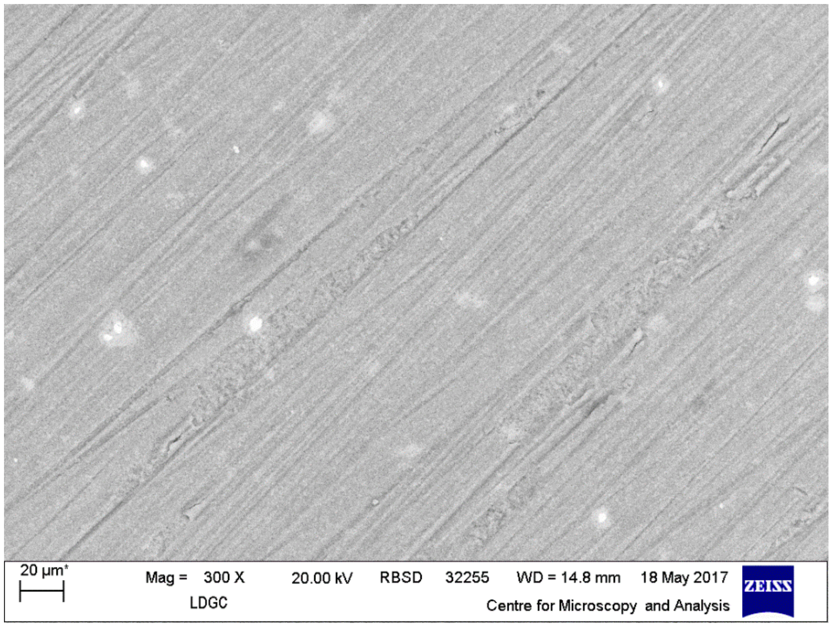

Figure 9.4. Scanning electron micrograph (×300) of the debonded surface of a lithium disilicate glass-ceramic substrate which demonstrated adhesive failure for resin composite (Tetric EvoCeram).

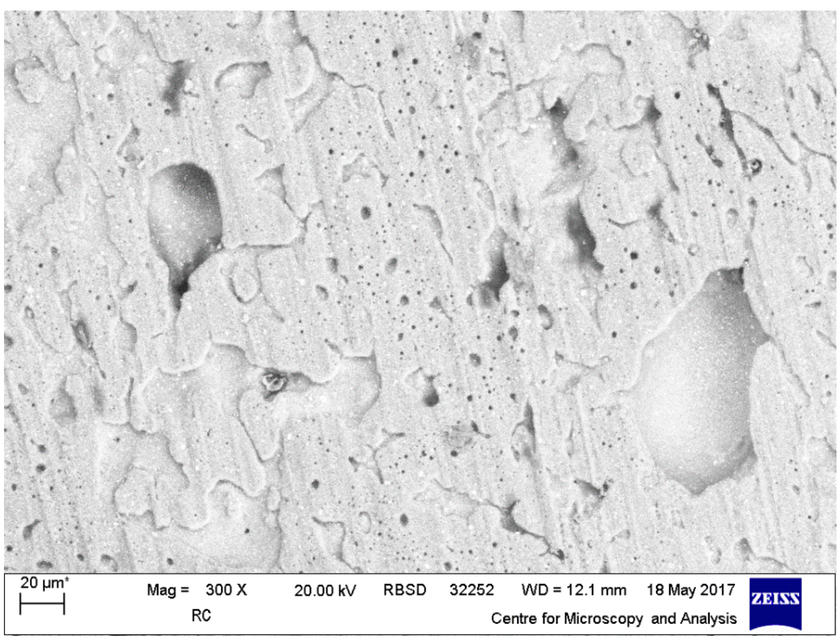

Figure 9.5. Scanning electron micrograph (×300) of the debonded surface of a resin composite (Tetric Evoceram) substrate which demonstrated adhesive failure for a lithium disilicate glass-ceramic (IPS e.max® Press).

9.5.4 Discussion

While recommended protocols vary between manufacturers of different adhesive resins and glass-ceramic materials to optimise bond strength, they generally contain a combination of some or all of the following, sandblasting, etching and/or silanating in conjunction with resin application. The ideal protocol for repair of glass-ceramic material is yet to be established. Etching with HF acid remains controversial and recommendations for its substitution with less aggressive acids have been made (Tylka and Stewart, 1994, Kussano *et al*., 2003, Filho *et al*., 2004).

Previous research has shown that a range of bond strength values may be achieved and inter-study comparisons are difficult to make. Bond strength values are dependent on the test methodology employed, the surface to which the resin is being bonded and storage conditions prior to testing (Oilo, 1993). While conflicting results prevail, the role of silane agent for the successful chemical adhesion of resin composite to glass-ceramic suggest that its use is indispensable (Filho *et al.,* 2004, Della Bona, 2009). Specimen preparation devoid of trimming or polishing after resin bonding is recommended to reduce stress in the adhesion zone (Della Bona *et al*., 2000).

The results obtained in this study are within the range of those reported in the literature and are comparable to those reported in another study (Panah *et al*., 2008) where similar materials, storage and testing methodologies were employed. One explanation for the high standard deviation may be attributed to the relatively rough surface topography (Figure 9.4) achieved with 180 grit SiC paper as opposed to a finer or polished surface finish. Potentially, grooves may be aligned to the polishing direction which act to promote retention through increased surface area. When the grooved surface is aligned perpendicular to the direction of force, it may enhance retention of the resin composite cylinder and increase the resistance to an applied shear force. The converse may occur when the specimen alignment is rotated through 90°, thus giving rise to high standard deviations. Additionally, porosity at the surface of the resin composite is evident (Figure 9.5), this could be related to the reduced wettability of the resin composite (Tetric Evoceram) to the glass-ceramic surface due to its higher viscosity compared with a flowable resin composite. The mode of failure was adhesive for all of the specimens, it is recommended that the mode of failure is reported when bond strength testing is performed (Panah *et al*., 2008, Oilo, 1993). This permits a more complete analysis of failure from the adhesion zone to be made, whereby the 'weakest link' can be identified thus permitting thorough assessment of the fracture process.

The manufacturer of IPS e.max® Press (Ivoclar Vivadent, IPS e.max® Press, Monolithic solutions 2014) contraindicate grit blasting the intaglio surface of a restoration prior to surface etching and silane application. Grit blasting can damage and weaken the ceramic restoration by introducing microcracks, in addition to this, abrasive damage can be sufficiently significant to erode the marginal integrity of the restoration which may result in clinical rejection. The manufacturer also recommends the application of 5% HF acid for 20 sec to the intaglio surface, followed by silane application prior to cementation. HF acid etching selectively removes the glass phase of LDGC, this may be responsible for the lower bond strength achieved in the absence of a silane bonding agent, since the silica has been removed as a result of the etching process the resin composite does not chemically bond with the remaining LD crystals. The bond strength increases when a silane agent is applied as this provides the silica component required for optimal bonding.

The durability of bonding in the long-term is an additional consideration given the complex environment of the oral cavity where it must withstand chemical, thermal and mechanical conditions (Blatz *et al*., 2003). It is recommended that, thermocycling regimes are employed to simulate these conditions. Aging regimes which include thermocycling, water storage and loading generally decrease bond strength values (Ozcan, 2009).

Acceptable mean SBS results, within the range of values reported in the literature for similar materials and test conditions were obtained in the current study. Limitations to this study were that, loading was applied in a monotonic direction, unlike the cyclic loading found intraorally and an ageing protocol which accounted for the rigours (moisture and thermal fluctuations) of the oral environment was not employed. It is postulated that the value obtained for SBS in the current study would decrease after the application of an ageing regime.

9.5.5 Conclusion

The results obtained from the bonding protocol used in this study are comparable to those reported in the literature for similar materials and test conditions. The protocol is therefore considered suitable for the repair of endodontic access cavities in a lithium disilicate glass-ceramic crown material.

9.5.6 Relevance of this Section in the context of the Thesis

The proposed stress state for the resin composite repair material for its intended use in Chapter 4 is illustrated in Figure 9.6. A monotonic load will be applied using a ring-on-ring test apparatus (ASTM C1499-05) to determine the EBFS of lithium disilicate glass-ceramic (IPS emax® Press) disc specimens after they have been subjected to a simulated endodontic access cavity. The flexural strength of specimens with a resin composite endodontic access cavity repair analogous to the clinical scenario will also be investigated. The resin composite will be subjected to, compressive stress above and tensile stress below, the neutral axis of bending as illustrated in Figure 9.6.

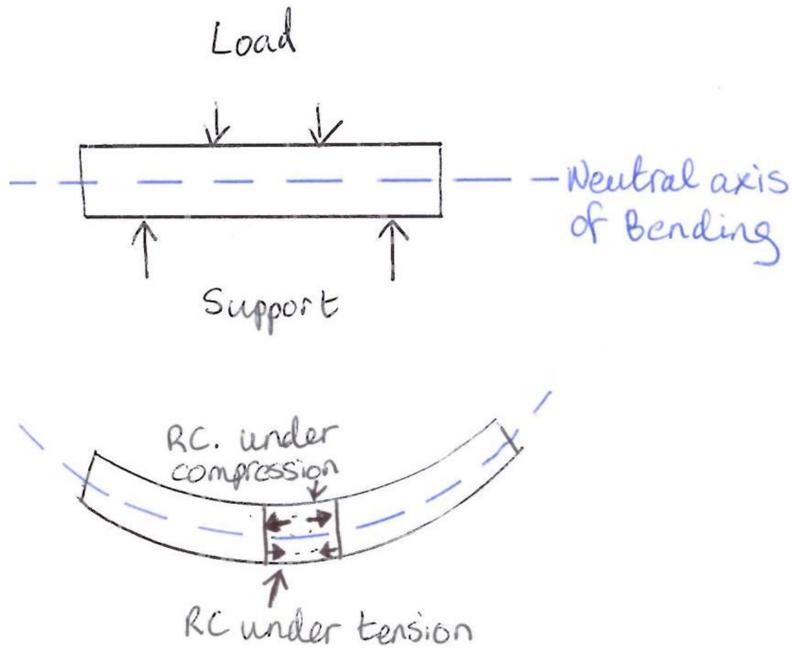

Figure 9.6. a) Schematic diagram which portrays the support and load conditions in an EBFS test for flat plate ceramic specimens. b) The stress state in relation to the neutral axis of bending during the flexure test, of the resin composite repair within the representative endodontic access cavity in a glass-ceramic disc specimen. The resin composite material is under compression in the load surface and under tension in the support surface.

9.5.7 References

Blatz MB, Sadan A, Kern M. Resin-ceramic bonding: a review of the literature. Journal of Prosthetic Dentistry 2003; 89:268-74.

Della Bona A, Anusavice KJ, Shen C. Microtensile strength of composite bonded to hot-pressed ceramics. Journal of Adhesive Dentistry 2000; 4:305-13.

Della Bona A. Important aspects of bonding resin to dental ceramics. Journal of Adhesion Science and Technology 2009; 23:1163-76.

Filho AM, Vieira LC, Araújo E, Monteiro Júnior S. Effect of different ceramic surface treatments on resin microtensile bond strength. Journal of Prosthodontics 2004; 13:28-35.

Kussano CM, Bonfante G, Batista JG, Pinto JH. Evaluation of shear bond strength of composite to porcelain according to surface treatment. Brazilian Dental Journal 2003; 14:132-5.

Oilo G. Bond strength testing--what does it mean? International Dental Journal 1993; 43:492-8.

Ozcan M, Valandro LF, Amaral R, Leite F, Bottino MA. Bond strength durability of a resin composite on a reinforced ceramic using various repair systems. Dental Materials 2009; 25:1477-83.

Panah FG, Rezai SM, Ahmadian L. The influence of ceramic surface treatments on the micro-shear bond strength of composite resin to IPS Empress 2. Journal of Prosthodontics 2008; 17:409-14.

Tylka DF, Stewart GP. Comparison of acidulated phosphate fluoride gel and hydrofluoric acid etchants for porcelain-composite repair. Journal of Prosthetic Dentistry 1994; 72:121-7.

Designation: C 1499 – 05

Standard Test Method for Monotonic Equibiaxial Flexural Strength of Advanced Ceramics at Ambient Temperature[1]

This standard is issued under the fixed designation C 1499; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the determination of the equibiaxial strength of advanced ceramics at ambient temperature via concentric ring configurations under monotonic uniaxial loading. In addition, test specimen fabrication methods, testing modes, testing rates, allowable deflection, and data collection and reporting procedures are addressed. Two types of test specimens are considered: machined test specimens and as-fired test specimens exhibiting a limited degree of warpage. Strength as used in this test method refers to the maximum strength obtained under monotonic application of load. Monotonic loading refers to a test conducted at a constant rate in a continuous fashion, with no reversals from test initiation to final fracture.

1.2 This test method is intended primarily for use with advanced ceramics that macroscopically exhibit isotropic, homogeneous, continuous behavior. While this test method is intended for use on monolithic advanced ceramics, certain whisker- or particle-reinforced composite ceramics as well as certain discontinuous fiber-reinforced composite ceramics may also meet these macroscopic behavior assumptions. Generally, continuous fiber ceramic composites do not macroscopically exhibit isotropic, homogeneous, continuous behavior, and the application of this test method to these materials is not recommended.

1.3 Values expressed in this test method are in accordance with the International System of Units (SI) and Practice E 380.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:* [2]

C 1145 Terminology of Advanced Ceramics

C 1239 Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics

C 1259 Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio for Advanced Ceramics by Impulse Excitation of Vibration

C 1322 Practice for Fractography and Characterization of Fracture Origins in Advanced Ceramics

E 4 Practices for Force Verification of Testing Machines

E 6 Terminology Relating to Methods of Mechanical Testing

E 83 Practice for Verification and Classification of Extensometer System

E 337 Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)

E 380 Practice for Use of International System of Units (SI) (The Modernized Metric System)

F 394 Test Method for Iron in Trace Quantities Using the 1,10-Phenanthroline Method[3]

3. Terminology

3.1 *Definitions*—The definitions of terms relating to biaxial testing appearing in Terminology E 6 and Terminology C 1145 may apply to the terms used in this test method. Pertinent

[1] This test method is under the jurisdiction of ASTM Committee C28 on Advanced Ceramics and is the direct responsibility of Subcommittee C28.01 on Mechanical Properties and Performance.

Current edition approved June 1, 2005. Published June 2005. Originally approved in 2001. Last previous edition approved in 2004 as C 1499 – 04.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Withdrawn.

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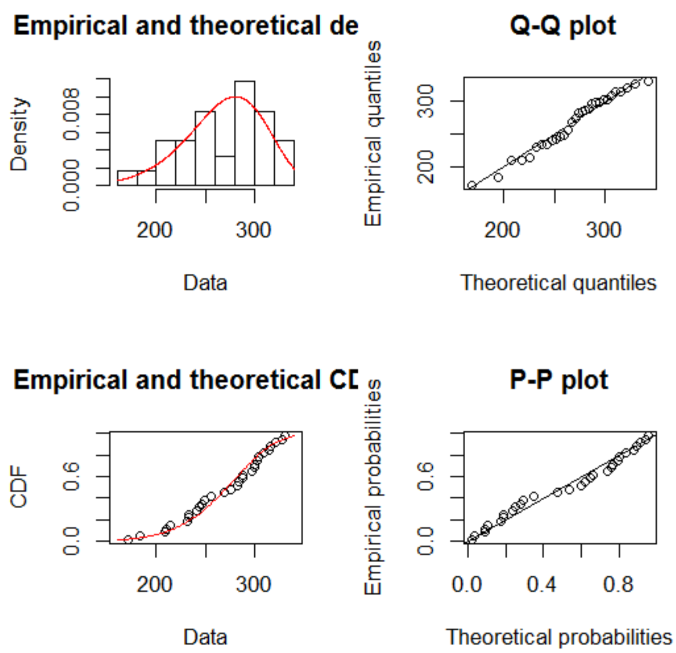
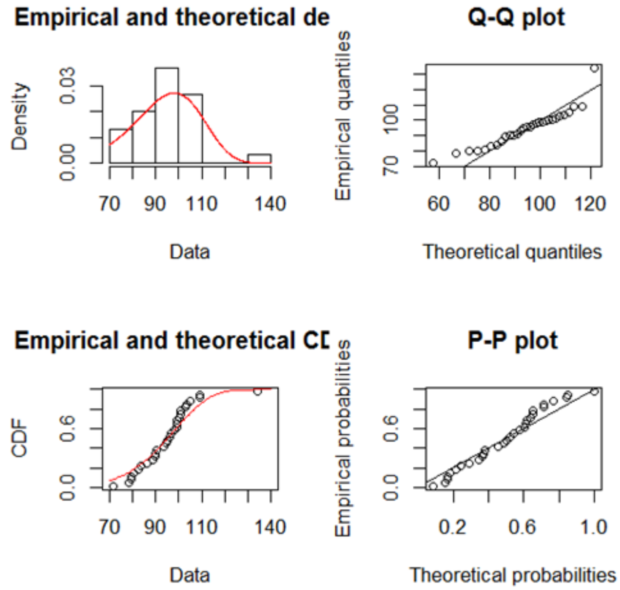
9.7 Supplemental statistical data for Chapter 4.

Check for Weibull fit of data from Chapter 4.

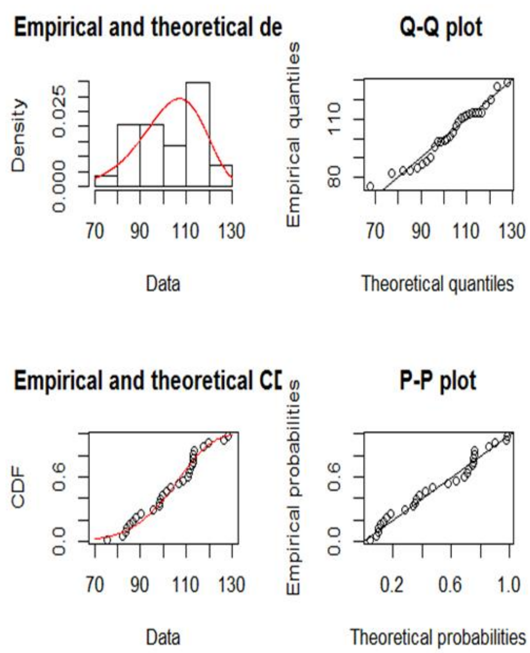
Four plots were examined for each group (A-G): 1) Empirical and theoretical density, 2) Q-Q plot, 3) Empirical and theoretical CDF and 4) P-P plot. Plots indicate that data (for each group) approximately follow the Weibull distribution. The four plots for each group are displayed below.



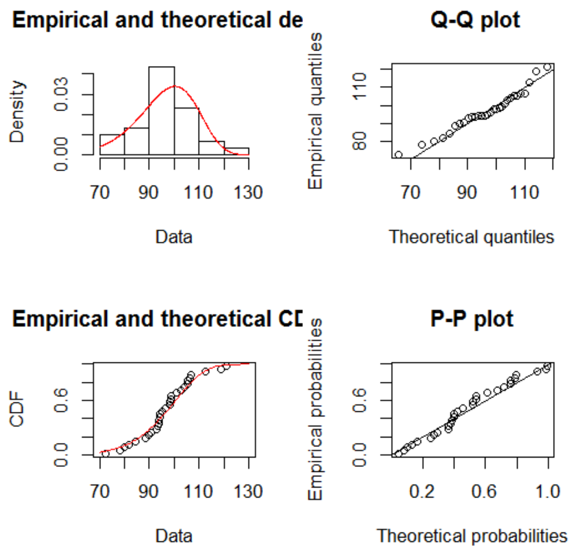
Group A (Intact LDGC disc specimens)



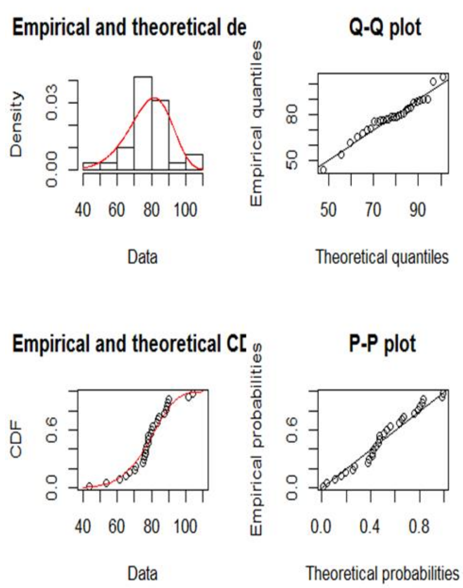
Group B (3 mm access cavity LDGC disc specimens)



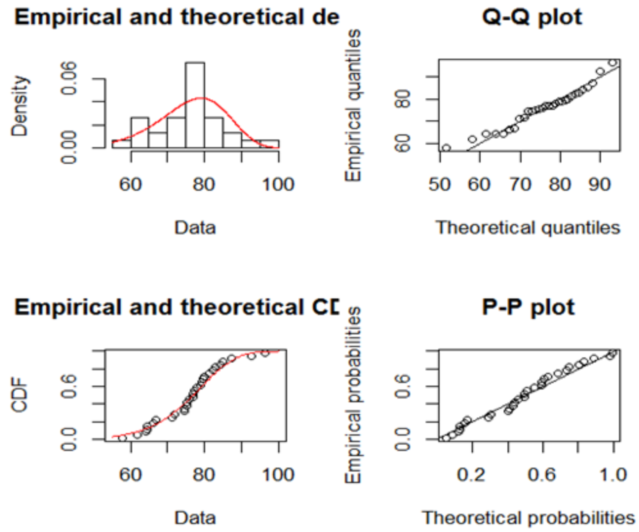
Group C (3 mm access cavity LDGC disc specimens repaired with low MOE resin composite)



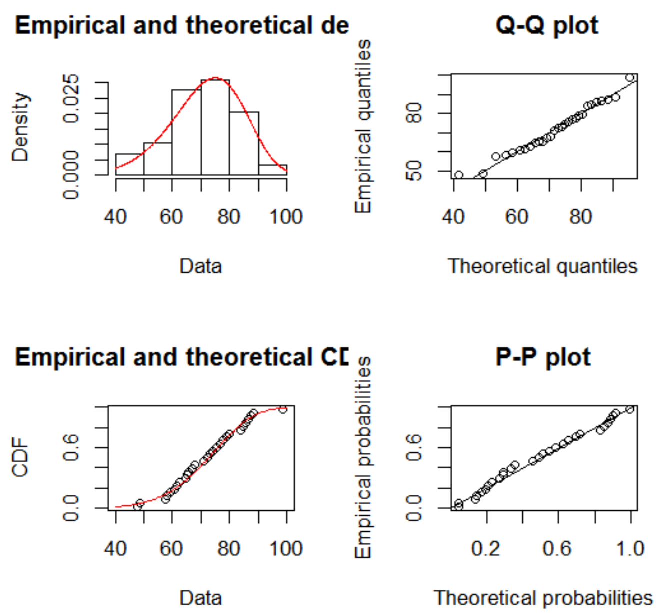
Group D (3 mm access cavity LDGC disc specimens repaired with high MOE resin composite)



Group E (5 mm access cavity LDGC disc specimens)



Group F (5 mm access cavity LDGC disc specimens repaired with low MOE resin composite)



Group G (5 mm access cavity LDGC disc specimens repaired with high MOE resin composite)

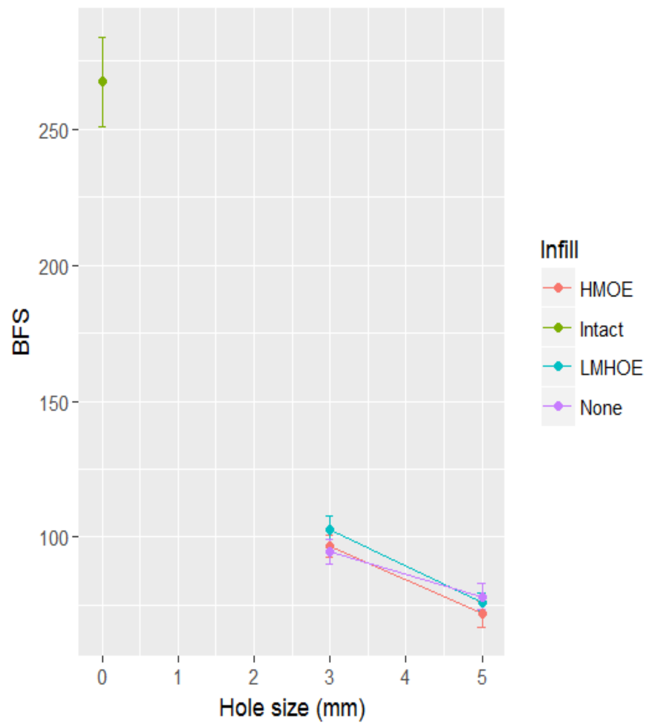


Figure 9.7 Mean EBFS (and corresponding 95% confidence interval) for different resin composite repair material and access cavity size (All groups A-G included).

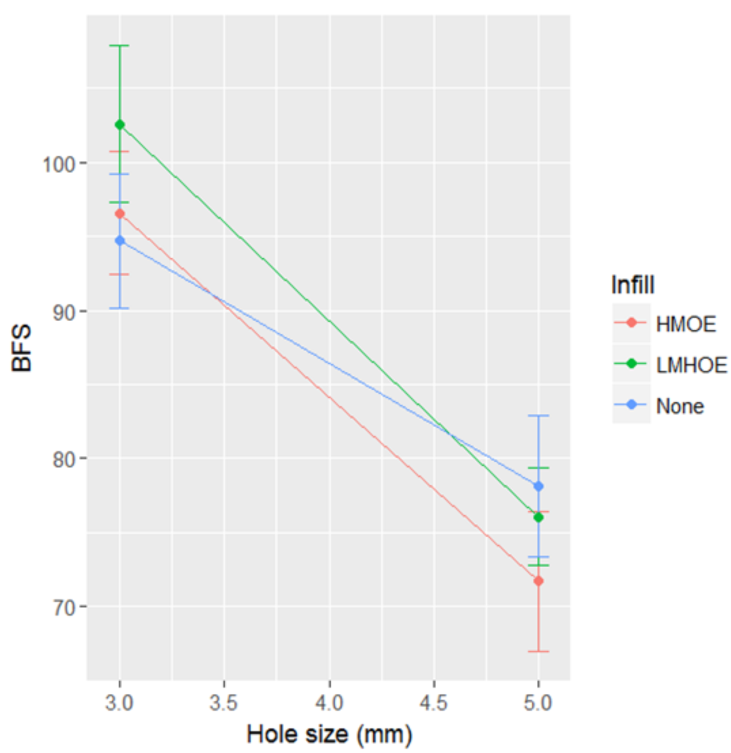


Figure 9.8 Mean EBFS (and corresponding 95% confidence interval) for different resin composite repair material and access cavity size (excluding Intact group A).

9.8 Supplemental statistical data for Chapter 5.

Assuming there are 5 groups and number per group is fixed at 10				
Alpha	Power	Number per group	Total specimen size	Effect size
0.05	0.80	10	50	0.51
0.05	0.90	10	50	0.59
0.05	0.95	10	50	0.64
Assuming there are 5 groups and number per group is fixed at 15				
Alpha	Power	Number per group	Total specimen size	Effect size
0.05	0.80	15	75	0.41
0.05	0.90	15	75	0.47
0.05	0.95	15	75	0.51

Table 9.8.1. Specimen Size estimates

- Alpha denotes the probability of a Type 1 error; - Power denotes 1-the probability of a Type 2 error;

- A Type 1 error is the probability of finding an effect that is not there (i.e. rejecting the null when it is true)

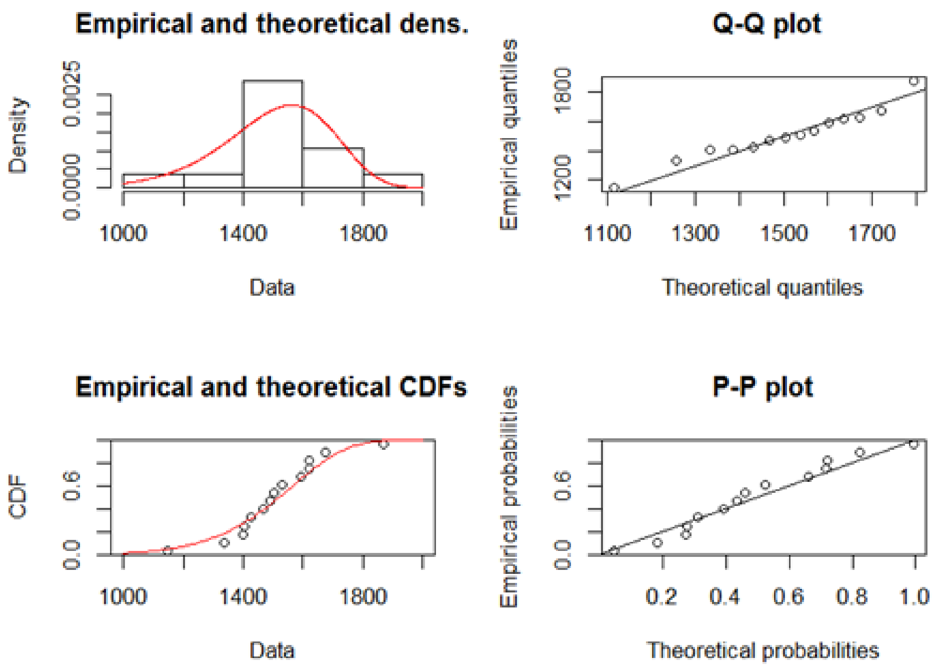
- A Type 2 error is the probability of finding no effect when there is an effect (i.e. fail to reject the null when it is false)

- Effect sizes, according to Cohen suggest that 0.1 represents small effect size and 0.2 medium effect size and 0.4 represent large effect size.

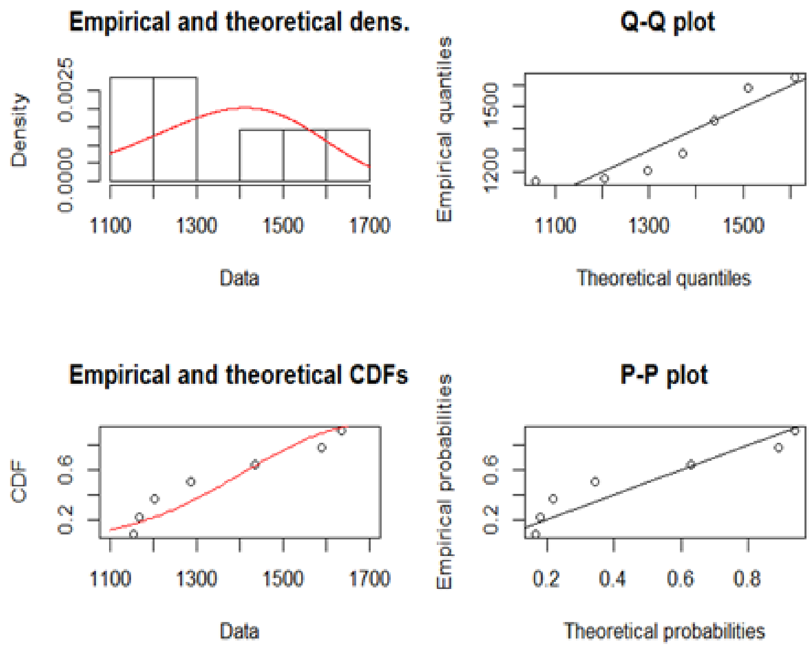
Note: Resource limitations restricted the number of specimens to 75 (i.e. 15 per group)

Check for Weibull fit of data from Chapter 5.

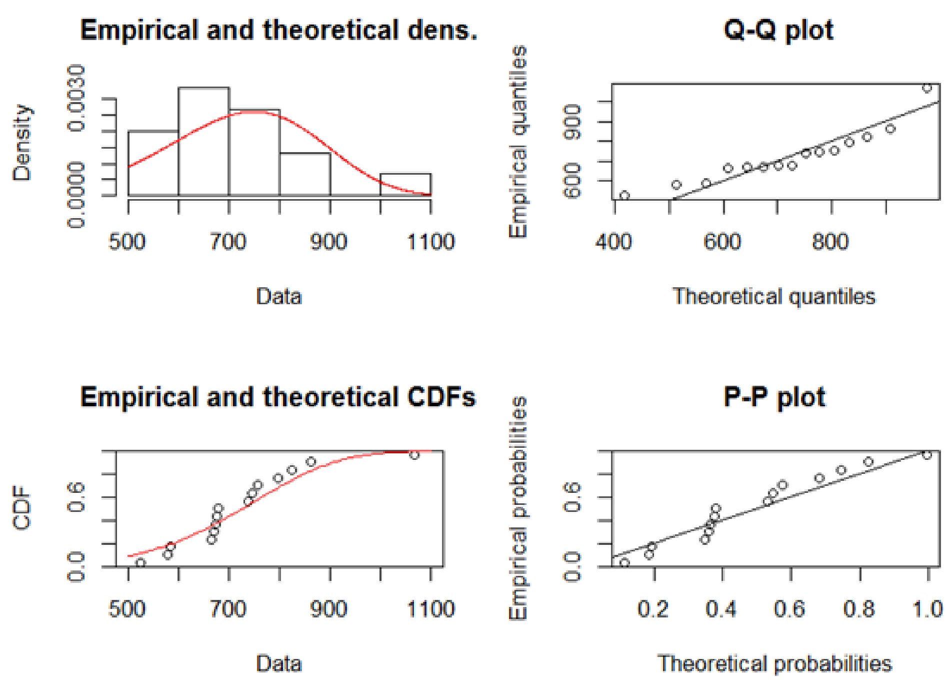
Four plots were examined for each group (A-E): 1) Empirical and theoretical density, 2) Q-Q plot, 3) Empirical and theoretical CDF and 4) P-P plot. Plots indicate that data (for each group) approximately follow the Weibull distribution. The four plots for each group are displayed below.



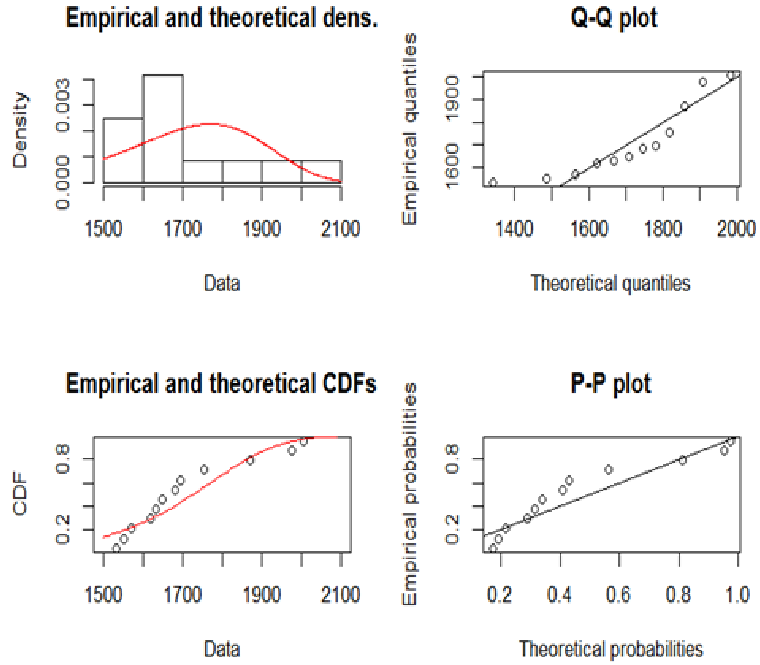
Group A (Intact LDGC crowns)



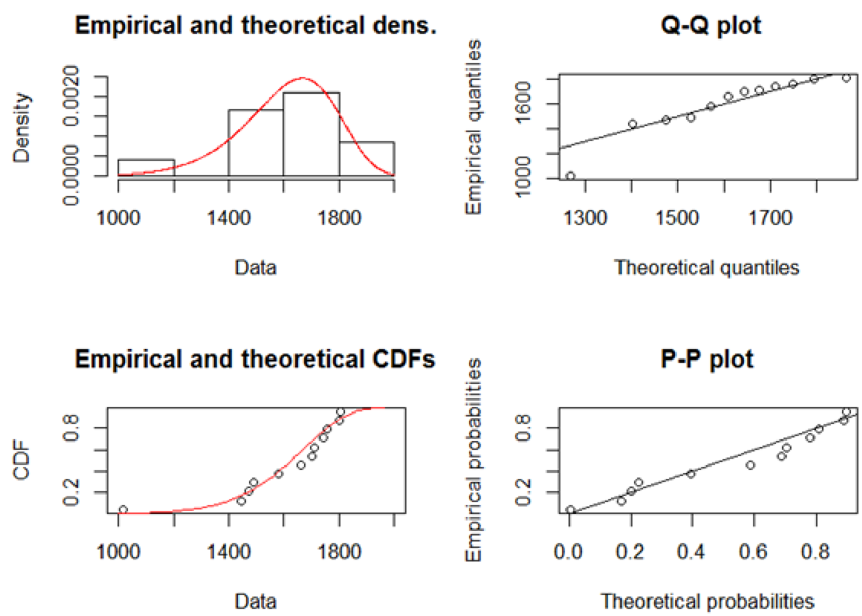
Group B (LDGC crown with small rhomboidal access cavity-unrestored)



Group C (LDGC crown with large rectangular access cavity-unrestored)



Group D (LDGC crown with small rhomboidal access cavity repaired with resin composite)



Group E (LDGC crown with large rectangular access cavity repaired with resin composite)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	Sig
Cavity	2	610840	305420	10.125	0.0004363	***
Residuals	30	904952	30165			

Table 9.8.2. One-way Analysis of Variance to compare Groups A, B, D. Significant codes: 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	Sig
Cavity	2	6554350	3277175	105.5	3.078e-16	***
Residuals	38	1180421	31064			

Table 9.8.3. One-way Analysis of Variance to compare Groups A, C, E. Significant codes: 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	Sig
Cavity	1	2430985	2430985	77.399	4.445e-11	***
Repair	1	4976254	4976254	158.438	7.636e-16	***
Cavity: Repair	1	712846	712846	22.696	2.282e-05	***
Residuals	42	1319149	31408			

Table 9.8.4. Two-way Analysis of Variance to compare Groups B, C, D, E. Significant codes: 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**

9.8.1 Modulus of elasticity of epoxy resin die material conversion from Shore-D hardness value to Young's modulus (MPa).

(https://sciencing.com/convert-durometer-youngs-modulus-7941189.html Date accessed 15/3/2018)

= EXP ((Shore-D Durometer + 50) * 0.0235-0.6403)

= EXP ((90+ 50) * 0.0235-0.6403)

= 14.15 MPa