produces a ceramic with the final shade and desired high strength. Table 4 shows the physical properties of IPS e.max.

Partially crystalized IPS e.max CAD

The microstructure consists of 40% lithium metasilicate crystals (Li_2SiO_3) embedded in a glassy phase. The grain size of the platelet-shaped crystals is in the range of 0.2 to 1.0 µm. The etched-out areas in Figure 15 show the lithium metasilicate crystals.

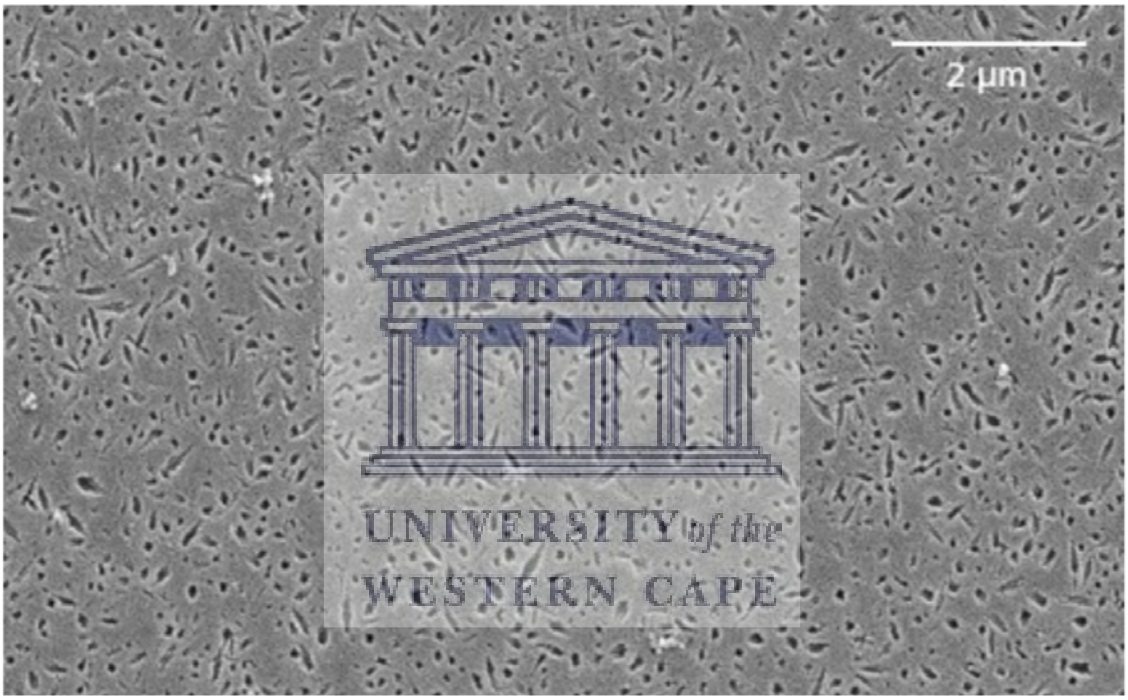


Figure 15: SEM of IPS e.max CAD Lithium-Metasilicate (blue phase) (with permission from Ivoclar Vivadent).

Fully crystalized IPS e.max CAD

After tempering at 850°C, the microstructure changes to consist of approximately 70% fine-grain lithium disilicate crystals, $Li_2Si_2O_5$, which are embedded in a glassy matrix. By etching with hydrofluoric acid vapour, the glassy phase is dissolved and the lithium disilicate crystals become visible (Figure 15). The physical properties of IPS.max CAD are shown in Table 4.

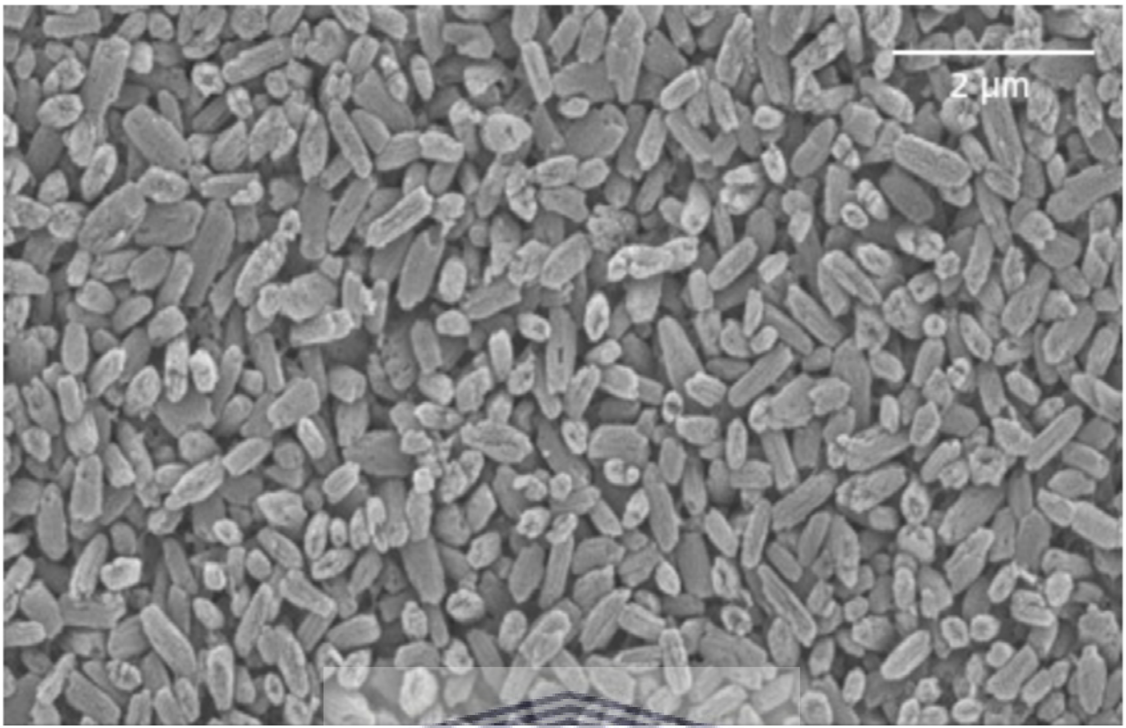


Figure 16: SEM of IPS e-max CAD Lithium-Disilicate (with permission from Ivoclar Vivadent technical specifications).

Table 3: Physical properties of IPS e.max CAD as documented by the manufacturer. (Ivoclar Vivadent, Schaan, 2005/06)

Physical properties	Partially crystallized state	Fully crystallized state
Physical properties Biaxial strength (ISO 6872)	130 ± 30 MPa	360 ± 60 MPa
Fracture toughness (SEVNB)	0.9 – 1.25 MPa m½	2.0 – 2.5 MPa m½
Vickers hardness	5400 ± 200 MPa	5800 ± 200 MPa

1.9.2 Cementation material

Variolink Esthetic DC

Variolink Esthetic (Ivoclar Vivadent, Schaan Lichtenstein) is a colour-stable, adhesive luting system for the permanent cementation of glass-ceramic, lithium disilicate glass-ceramic, composite and oxide ceramic restorations (inlays, onlays and veneers). Variolink Esthetic is offered in two versions; Variolink Esthetic LC, which is purely light-curing, and Variolink Esthetic DC which is dual-curing. Table 5 summarizes the indications for use of Variolink Esthetic DC and LC according to the manufacturer's guidelines. Variolink Esthetic DC can be used with opaque restorations, whereas the LC variant should only be used for thin restorations with a thickness less than 2mm, and sufficient translucency (e.g. restorations made of IPS e.max Press and CAD HT). For this study, a DC cement was used.

Table 4: Indications for use of Variolink Esthetic LC and DC. (Braziulis, 2014)

✓" indicates where the cements can be used. "?" Indicates where reduced thickness inlays, onlays and crowns can be used in combination with LC cements if the material thickness allows for sufficient light penetration for complete polymerisation.

	Vaiolink Esthetic LC	Variolink Esthetic DC
Inlays	?	✓
Onlays	?	✓
Partial crowns	?	✓
Occlusal veneers	✓	✓
veneers	✓	✓
crowns	✗	✓
bridges	✗	✓

Composition of Variolink Esthetic

The monomer matrix of Variolink Esthetic is composed of urethane dimethacrylate and other methacrylate monomers. The inorganic fillers are ytterbium trifluoride and spheroid mixed oxide. Initiators, stabilizers and pigments are additional ingredients.

Adhese Universal

Adhese Universal (Ivoclar Vivadent, Schaan Lichtenstein) is a newly marketed universal adhesive system indicated for the bonding of porcelain and composites. This single-component, light-cured adhesive is used for both direct and indirect bonding procedures. Adhese Universal is based on the Adhese product family and Multilink Primer. It contains methacrylate, ethanol, water, highly dispersed silicon dioxide, initiators and stabilizers.

Adhese Universal is indicated for bonding or repairing light-cured composite and compomer restorations, for core build ups with light-, self- and dual-curing composites, for the adhesive cementation of indirect restorations with light- or dual-curing luting composites, for sealing prepared tooth surfaces before the temporary / permanent cementation of indirect restorations (e.g. immediate dentine sealing / dual-bonding technique) and for desensitizing hypersensitive cervical areas. As Adhese Universal is always light-cured, it is contraindicated in situations where sufficient illumination cannot be ensured, e.g. the cementation of root canal posts.

Adhese Universal is indicated for use with the total-etch, self-etch techniques and with dual-cure materials without a separate activator. It is not, however, indicated as a separate primer for restorative substrates according to the manufacturer.

Due to the adhesive acidic monomers inhibition of the polymerization of auto-cured and dual-cure composite luting cements, Adhese Universal requires polymerisation before seating of indirect restorations. The subsequent layer thickness can be an issue when seating indirect restorations. Adhese Universal is always "thinned out" with dispersed air (which is aided by the inclusion of thixotropic silica) and subsequently light-cured before seating indirect restorations – eliminating the need for an additional dual-cure activator. Curing Adhese Universal immobilizes the acid monomers and allows good polymerization at the adhesive-cement interface without a separate activator. The cured adhesive exhibits a layer thickness of < 10µm on bovine dentine, enabling the seating of even very tight-fitting indirect restorations and, when combined with Variolink II luting composite, there is an increase in inlay elevation of < 50 µm, which will not negatively affecting accuracy of fit (Ivoclar-Vivadent-AG, 2013).

In addition, the shear bond strength of Adhese Universal to aged composites was evaluated in in-house studies conducted by Ivoclar-Vivadent (Ivoclar-Vivadent-AG, 2013). All the composites achieved shear bond strength values of around 25-26 MPa. The bond strength exceeded the cohesive strength of the material with 100% of the samples undergoing cohesive failure in the test.

Table 5: A summary of the indications for universal bonding agents on the market (adapted from Ivoclar-Vivadent-AG, 2013). ✓ indicates where the cements can be used

Product	Total-etch	Self-etch	Dual cure	Bonding to LiDi	Bonding to Zirconia
All-bond unversal	✓	✓	✓	✓	✓
Peak universal	✓	✓	×	×	×
Adhese Universal	✓	✓	✓	✓	✓
Optibond	×	✓	✓	✓	✓

Monobond etch and prime

Monobond etch-and-prime (ME&P - Ivoclar Vivadent, Schaan, Lichtenstein) is a novel single bottle ceramic primer, which allows for etching and silanisation of the glass ceramic surface in one step. It contains a trimethoxypropyl methacrylate for silanisation and a new polyfluoride for the etching step. The etching creates a roughness pattern, which is less pronounced than with hydrofluoric (HF) gel, but as efficient for bonding (Wille, Lehmann and Kern, 2017).

Ammonium polyfluoride reacts with the silicon on the glass ceramic without the release of HF, due to the high chemical affinity between silicon and fluoride (Roman-Rodriguez *et al.*, 2017). After the extra-oral application, the remaining liquid is thoroughly rinsed off. Once dry, a thin silane layer in molecular scale remains at the luting surface, which reacts via the methacrylate group with the luting composite during curing (Roman-Rodriguez *et al.*, 2017).

During in-house studies, the manufacturer evaluated the bond strength of Monobond etch-and-prime on various ceramic substrates (Völkel and Braziulis, 2015). Monobond etch-and-prime produced a high aging-resistant adhesive bond on various ceramic material, similar to that produced by the silane agent Monobond Plus after hydrofluoric acid etching (Völkel & Braziulis, 2015).

1.10 Methods

Forty routinely extracted human molar teeth were used in this study, after each patient received an information sheet and patient consent was obtained (Appendix 1 and 2). All molar teeth without any caries or fillings were cleaned and stored in a 0.1% thymol solution prior to use. The roots of the teeth were then embedded in custom made standard UPVC (unplasticized polyvinyl chloride) cylinders (Ø 15 mm) and positioned along their long axis with auto-polymerizing acrylic resin material (Technovit 4000, HeraeusKulzer, Wehrheim, Germany). They were positioned so that the cement-enamel junction was located 2 mm above the level of the embedded resin.

Specimens were divided randomly into two groups (*n* = 20 each) (figure 17.

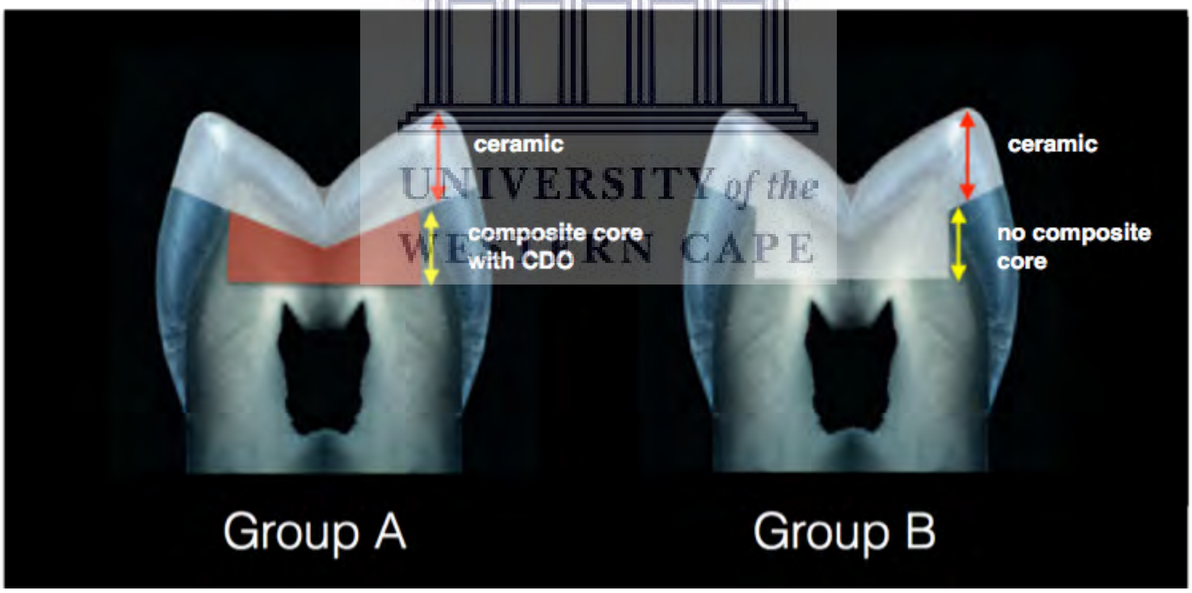


Figure 17: Preparation design of Groups A & B .

Group A has been prepared with a class I cavity that is filled with composite.

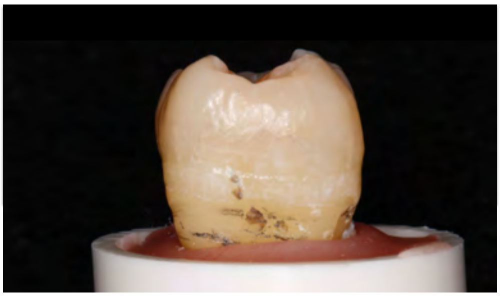
In Group B the class I cavity is left unfilled and was replaced by monolithic ceramic only.

Group A: Coronal crown preparation (butt joint) was prepared, using a pre-shaped diamond wheel under constant water cooling, until all central dentine was exposed and a circumferential enamel margin of at least 1mm was present (Figures 18a and 18b). An additional Class I cavity that included all the exposed dentine was prepared to a depth of 1mm from the central fissure using a round size 10 bur (Figures 18c and 18d). This was done to simulate the clinical situation where most teeth may present with Class I cavities. The prepared class one cavity was then restored with composite material (Tetric N-Ceram, Ivoclar Vivadent, Schaan, Liechtenstein) using a single bottle bonding system (Tetric N-Bond Universal, Ivoclar Vivadent, Schaan) (Figure 17e). A 130-degree preparation angle was maintained in the buccolingual and checked with a pre-shaped guide (Image 18f). The preparation was then smoothed and all sharp edges rounded.

Group B: Coronal crown preparation and Class I one cavity preparation as above. The Class I cavity was left unfilled (Figures 18g and 18h). A 130-degree preparation angle was maintained in the buccolingual using a pre-shaped gauge to 130 degrees. Preparations were smoothed and sharp edges rounded.

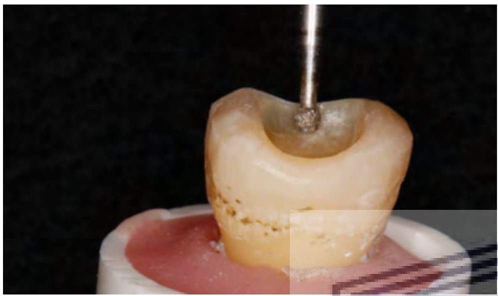
In both groups, the circumferential outline of the preparation was strictly within the enamel. An angle of 130° was maintained between the cusps.

Group A

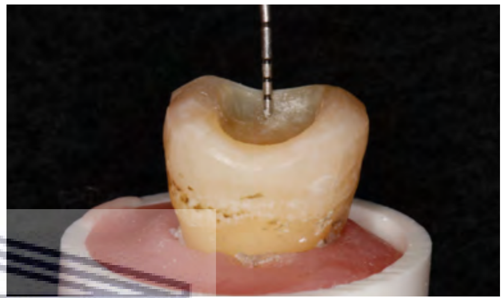


a) Unprepared tooth

b) confirmation of 130º inter-cuspal angle using a pre-shaped guide



c) class I cavity created using a no 10 round bur

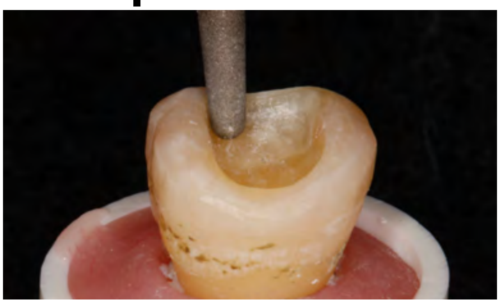


d) confirm of depth of cavity at 1mm using periodontal probe

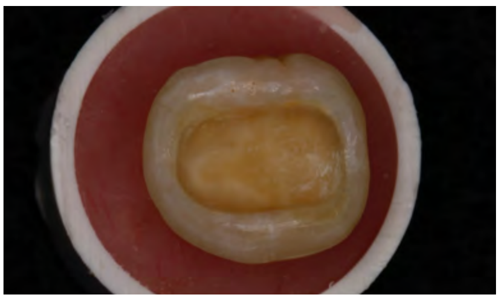
e) complete filling of Class 1 cavity using composite restorations

f) Final preparation checked using pre-shaped gauge

Group B



g) unfilled class I cavity smoothened for restoration



h) Final preparation

Figure 18 Laboratory process followed to create Group A and B preparations

The process of designing and adhesive placement of the CAD/CAM lithium disilicate restorations was then followed. A preliminary optical impression (CEREC Omnicam; Sirona Dental Systems GmbH, Bensheim, Germany) was made and the restoration designed (Figures 19a to f). The design and manufacturing of standardized occlusal veneers were done using the CEREC database and generated with the CEREC version 4.4 software (Sirona Dental Systems GmbH).

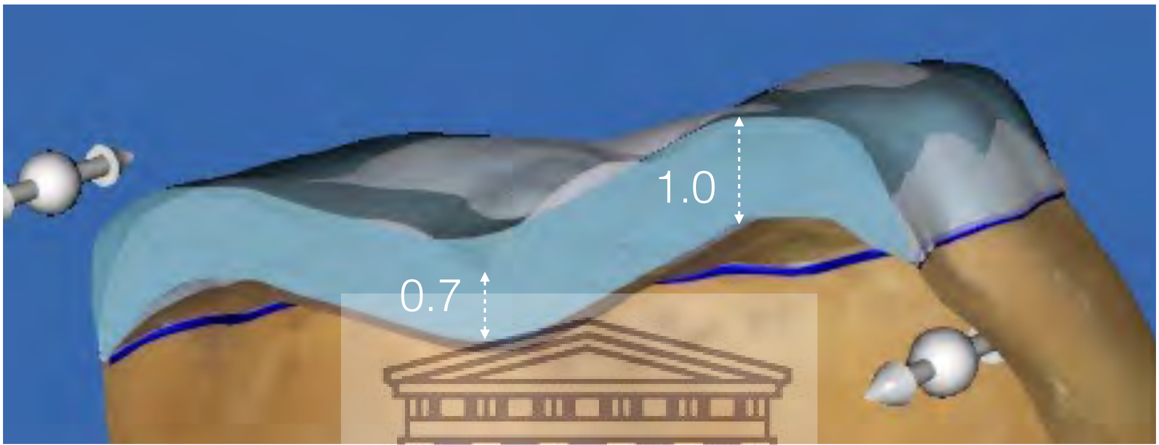
Table 6: Distribution of groups and their thicknesses

	Substrate	Ceramic thickness
Group A	Enamel and composite filled dentine cavity preparation	1mm at cusp with 0.7mm fissure depth
		0.8mm at cusp with 0.5mm fissure depth
Group B	Enamel and unfilled dentine cavity preparation	1mm at cusp with 1.7mm fissure depth
		0.8mm at cusp with 1.5mm fissure depth

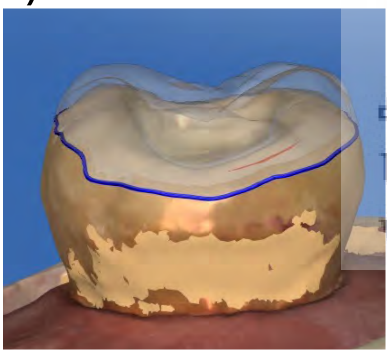
Each group (Groups A and B) were further divided into two groups based on the restorative ceramic thickness as shown in Table 9 For Group A1, there was a reduction of 1mm over the cusp and 0.7 in the fissure and for Group A2, there was a reduction of 0.8mm over the cusp and 0.5mm in the fissure. For Group B1, the reductions were 1mm over the cusp and 1.7mm in the fissure and for Group B2, the reductions were 0.8mmm over the cusp and 1.5mm over the fissure (Table 9). The additional 1mm of ceramic thickness over the fissure of Group B allowed for the restoration of the void created by the 1mm deep class 1 cavity that was left unfilled.

To standardise the study and in order to achieve a constant ceramic thickness, the occlusal surface received a semi-anatomic shaping. In the CAD/CAM software, the occlusal surface of the tooth was virtually elevated and then reduced again until the desired fissure thickness was obtained. Software design tools were used to create the defined cuspal height (Figures 19d and 19f).

a) b) c)



d)



e)

a) group A virtual model created using CEREC Omnicam digital scanner. Virtual restoration margin identified

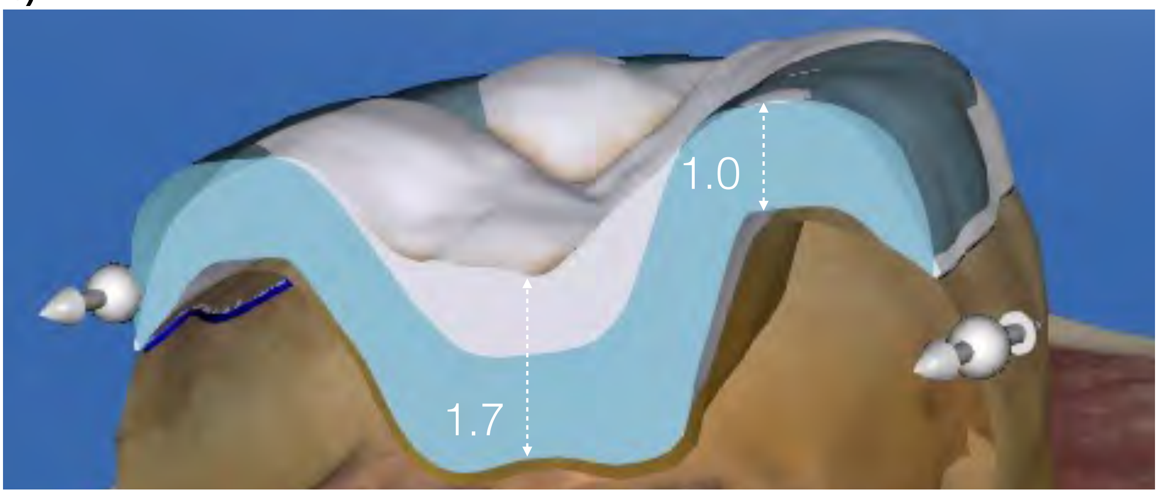
b) design of virtual restoration using CEREC design software

c) confirmation of restoration design using design software transparency

d) use of virtual minimal thickness guides (set at 1mm and shown in blue) to confirm thickness of restoration at 1mm over cusp and 0.7mm at fissure

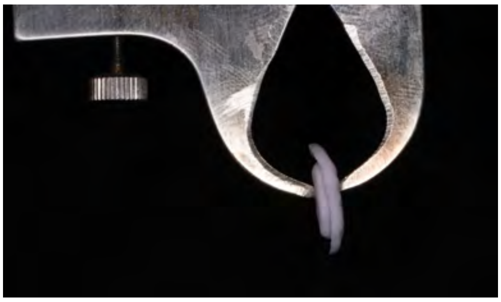
e) confirmation of design of group B restoration

f) confirmation of thickness of group B restoration at 1mm over cusp and 1.7mm over fissure

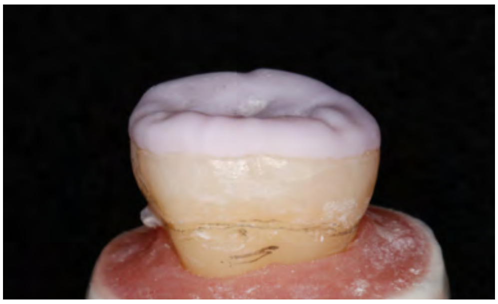


f)

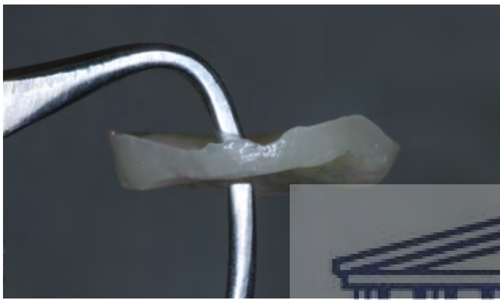
Figure 19: CAD/CAM design of restorations of Groups A and B.



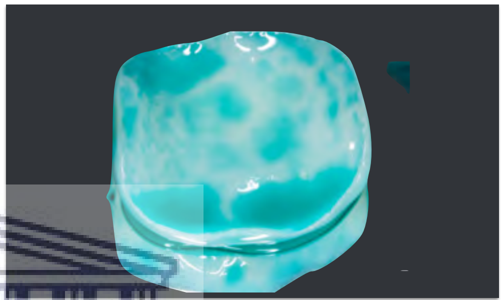
a) confirmation of thickness of ceramic using manual callipers



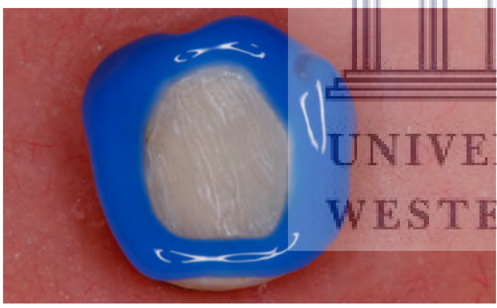
b) visual confirmation of fit of ceramic before crystallisation



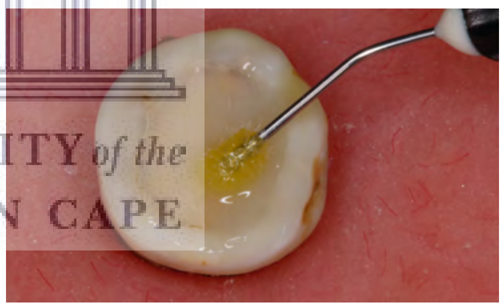
c) inspection of intaglio after crystallisation



d) Application of etch and prime to condition intaglio surface

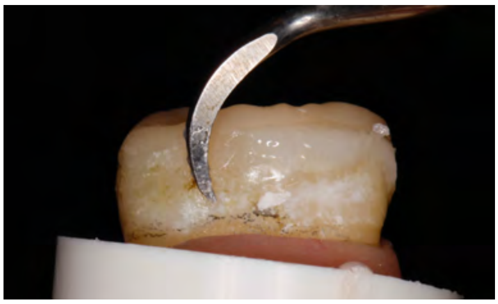


e) selective etch of enamel for 20 seconds



f) application of adhesive on tooth surface

g) cementation of ceramic



h) removal of excess cement after curing

Figure 20: Manufacture, conditioning and cementation of restorations.

The uncrystallised ceramic occlusal veneers were then milled out of lithium disilicate blocks (IPS e.max.CAD, Ivoclar Vivadent, Schaan, Liechtenstein) using the CEREC MCX Wet/Dry Milling Unit (Sirona Dental Systems GmbH). All restorations were milled in Fine Mode with the sprue at the lingual surface. Restorations were visually inspected for possible milling cracks and minimal thickness and fit was confirmed (Figures 20 and 20b). All restorations were then crystallized according to the manufacturer's specifications using a Programat CS2 (Ivoclar Vivadent) set for standard crystallization on setting no 1. After crystallisation and cooling, the restorations were polished using Eva Diapol and Eva Diacera polishing wheels.

During cementation, all enamel surfaces were pre-treated with 37% phosphoric acid for 20 seconds (Figure 20e). The preparation was then actively rinsed with water for 60 seconds and dried. A self-etching primer (Tetric N-Bond Universal, Ivoclar Vivadent, Liechtenstein) was applied onto the bonding surface of the tooth with an innovative application tip, Viva Pen (Ivoclar Vivadent, Lichtenstein) for 20 seconds (Figure 20f) and the surface gently air-dried. The bonding surface was then light-cured using a dental curing light (Bluephase Style, Ivoclar Vivadent, Schaan) for 10 seconds. Light output was checked prior to use with a CureRite device (Dentsply, USA) and was recorded at 1200mW/cm^2. This was checked after every five uses.

The bonding surfaces of the ceramic restorations were actively agitated for 20 seconds (with an additional waiting period of 40 seconds) using the self-etching glass ceramic primer (Monobond Etch-and-Prime Ceramic Primer, Ivoclar Vivadent, Lichtenstein). All restorations were thoroughly cleaned using water spray for 60 seconds and then air-dried (Figure 20d).

A dual cure luting composite (Variolink Esthetic, Ivoclar Vivadent) was dispensed from the automix syringe onto the intaglio surface of the restoration and onto the fissure area of the tooth. The restoration was positioned by hand and kept in place. After spot curing using a dental curing light (Bluephase Style, Ivoclar Vivadent) for two seconds per surface, all excess resin cement was removed (Figures 20g and 20h). All margins were covered with a glycerine air block (Liquid Strip, Ivoclar Vivadent) and light-cured for 20 seconds from all aspects (total of 180 seconds). After cleaning of excess cement from the margins (figure 20h), all margins were polishing using Eve Ecoceram polishing burs and specimens were stored in water for 24 hours at 37ºC in order to achieve complete curing.

After water storage, all specimens were thermo cycled 7500 times between 5ºC and 55ºC in water with a 30 second dwell time at each temperature. The specimens were then loaded in a universal testing machine (Zwick Z010/TN2A, Ulm, Germany). A steel bar with a 6mm ball end was centred on the main fissure of each specimen in order to apply the load evenly to the triangular ridges of the oral and buccal cusps. Additionally, a 0.6mm tin foil was placed between the ball end and the specimen in order to distribute the load homogenously. The stainless-steel bar descended at a crosshead speed of 1 mm/min while computer software (TestXpert II, Zwick, Ulm, Germany) recorded the load in Newton (N).

The specimens were loaded to intervals of 500N, 800N, 1000N, 1200N, 1500N, 1700N and 2000N. After each loading interval, the specimens were inspected for any sign of crack formation and photographed under standardized conditions at x1.5 magnification (Canon EOS 70D with Canon EF 100mm f/2.8L Macro IS USM Lens). Once crack formation was noted, the specimens were loaded to failure and the maximum load recorded. Two examiners were used to assess for any crack formation.

1.11 Data Analysis

Data was captured and exported into Statistical Package for the Social Science (SPSS) version 21 (IBM, USA) for statistical analysis. Kruskal Wallis analyses with group and thickness as independent variables were evaluated. The mean fracture values expressed in Newtons (N) were compared for statistical differences between the groups and a p value < 0.05 was considered as significantly different.

CHAPTER 4

Results

1.12 Fracture strength testing

When evaluating the maximum fracture values of the two preparation designs (group A and B) at two different restorative thicknesses (1mm with a fissure of 0.7mm, and 0.8mm with a fissure of 0.5mm), the following observations were noted:

Table 7: Dispersion in the observation of fractures

Group	Thickness	N	Mean	Standard Error of Mean	Minimum	Maximum	Range
A	1 mm	10	2460.70	100.02	2026.00	2965.00	939.00
	0.8 mm	10	1523.80	217.72	380.00	2340.00	1960.00
	Total	20	1992.25	158.57	380.00	2965.00	2585.00
B	1 mm	10	3142.60	328.35	1835.00	4560.00	2725.00
	0.8 mm	10	2591.80	280.63	1445.00	3967.00	2522.00
	Total	20	2867.20	219.50	1445.00	4560.00	3115.00

In general, Group B (ceramic only) restorations showed higher fracture resistance at a mean value of 2867N compared to that of Group A (composite core) with a mean value of 1992N.

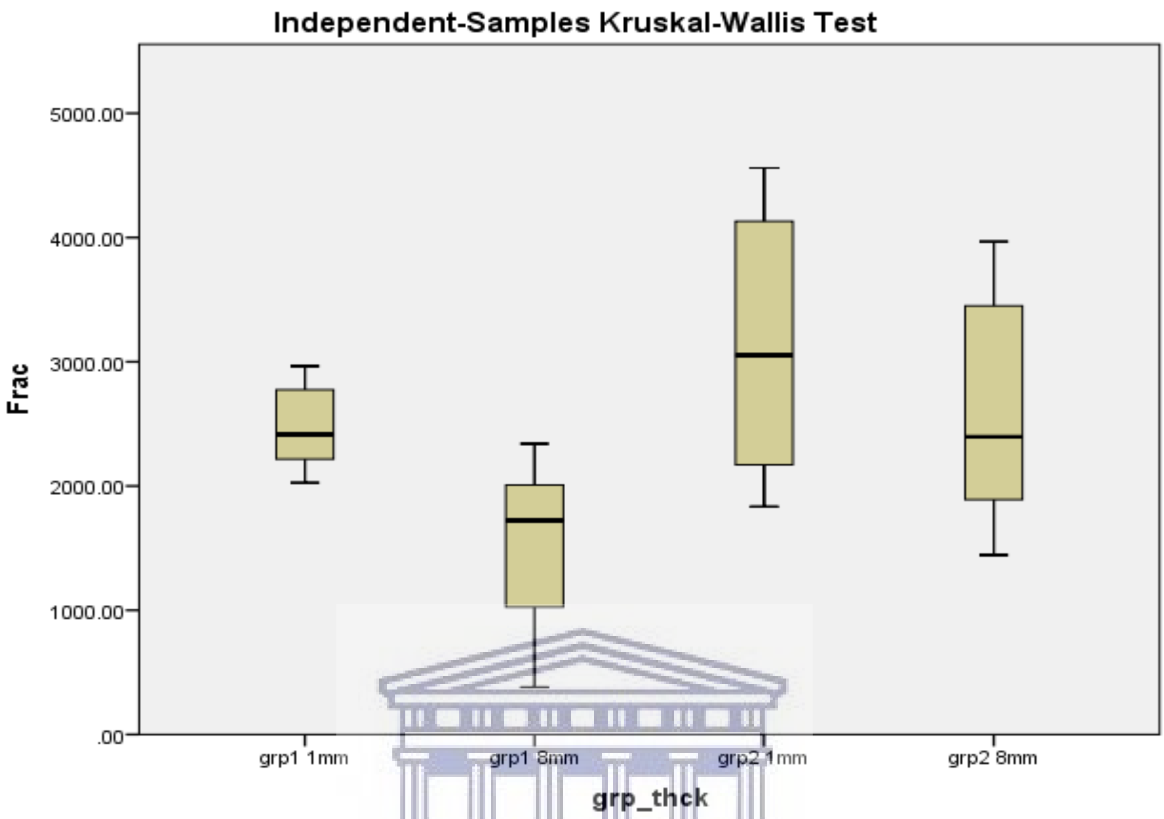


Figure 21: Results of Kruskal-Wallis analysis with group and thickness as independent variables shown in box plot. Fracture (Frac) and Group Thickness (Grp_thck)

The box plot of figure 21 shows the median, minimum and maximum fracture values as well as the upper and lower quartiles of the observed maximum fracture values.

Table 8: **Pairwise comparison of groups and thicknesses.**

Pairwise Comparisons of Groups and Thicknesses					
Grp A - Grp B	Test Statistic	Std. Error	St Test Statistic	Sig.	Adj. Sig.
Grp A 8mm-grp A 1mm	14.60	5.23	2.793	.005	.031
Grp B 8mm-grp B 1mm	5.20	5.23	.995	.320	1.000
Grp A 1mm-grp B 1mm	-4.30	5.23	-.822	.411	1.000
Grp A 8mm-grp B 8mm	-13.70	5.23	-2.620	.009	.053

Each row tests the null hypothesis that the Sample A and Sample B distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .05.

Intra-group variations in maximum fracture value

Group A (composite core preparation):

When evaluating the mean fracture values of Group A (composite core preparation) at the different porcelain thicknesses, there was a significant difference in the maximum fracture value between the 1.0mm and 0.8mm thick porcelain ($p < 0.05$, Kruskal-Wallis Test). The mean fracture value of 1.0mm porcelain thickness (2460 Newton) was significantly greater than that of 0.8mm porcelain thickness (1523 Newton).

Group B (no composite core):

When evaluating the fracture values of Group B (no composure core preparation) at the different porcelain thicknesses, there was no significant difference in the maximum fracture values of the two porcelain thicknesses ($p > 0.05$, Kruskal-Wallis Test). The mean fracture value at a thickness of 1.0mm porcelain thickness (3142 Newton) was not significantly different to that of 0.8mm porcelain thickness (2591 Newton).

Inter-group variations in maximum fracture value

Group A & B (1mm thickness):

When evaluating the fracture values of the 1mm thick porcelain restoration with two different preparation designs of Group A (class I cavity filled with composite core) and B (class I cavity with no composite core), no statistical significance was noted in the maximum fracture resistance ($p > 0.05$, Kruskal-Wallis test).

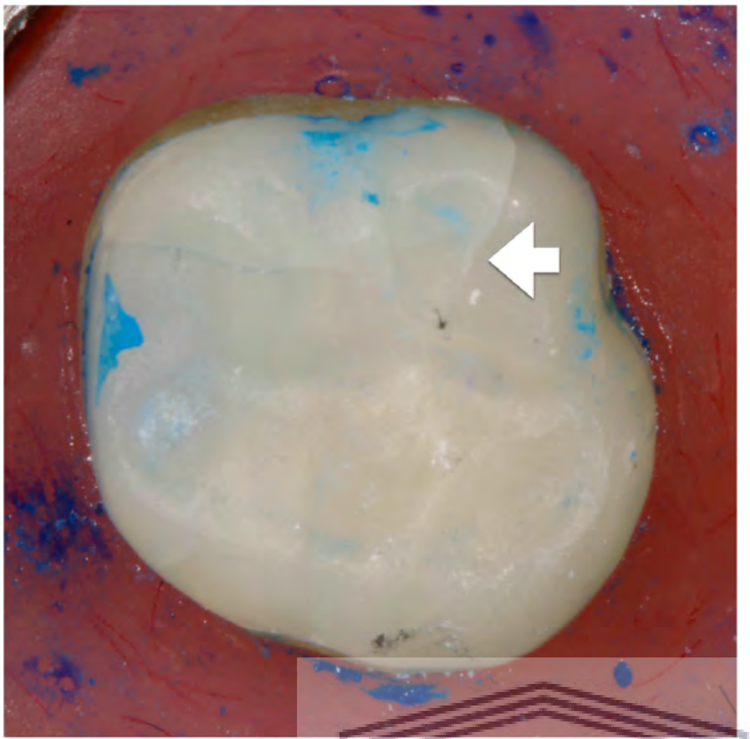
Group A & B (0.8mm thickness):

When evaluating the fracture values of the 0.8mm thick porcelain restoration with two different preparation designs of Group A (Class I cavity filled with composite core) and B

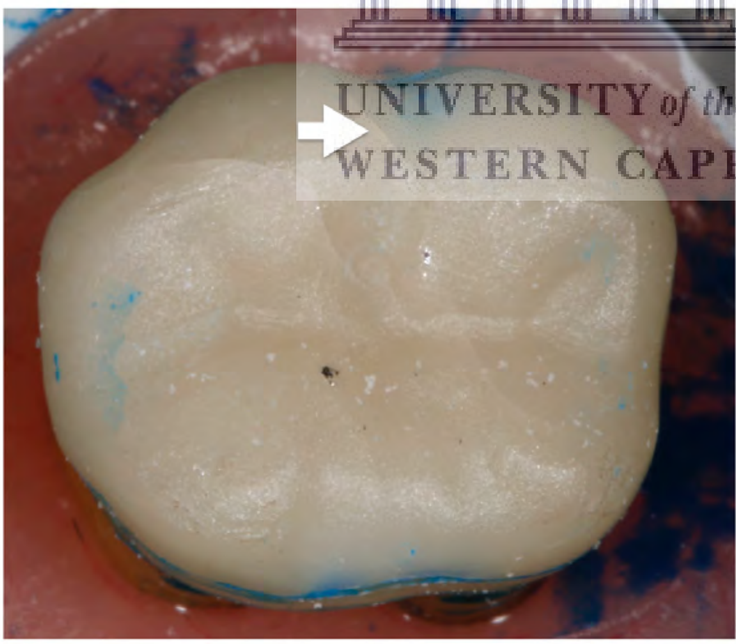
(Class I cavity with no composite core), a statistical significance was noted in the maximum fracture resistance ($p < 0.05$, Kruskal-Wallis test).

1.13 Load values at initial crack identification

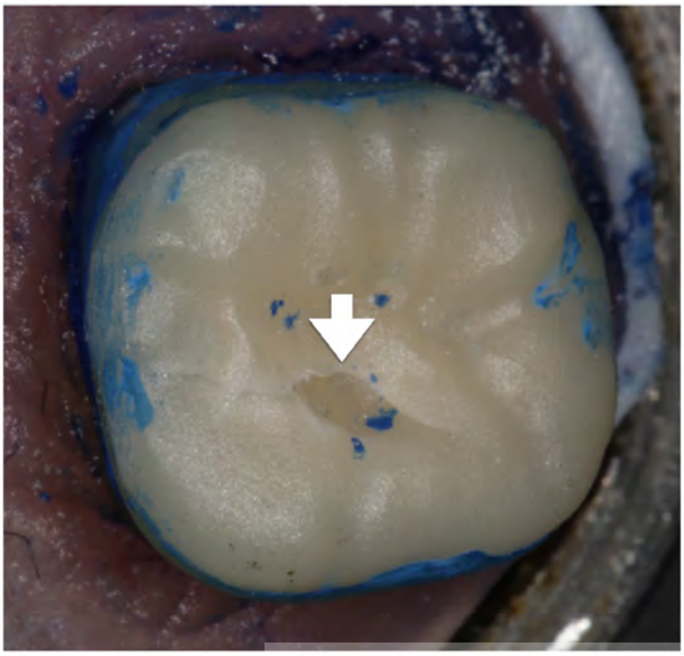
Each specimen was visually evaluated for the presence of any cracks at increasing load values of 500N, 800N, 1000N, 1200N, 1500N, 1700N and 2000N (Figure 22). With reported maximum masticatory forces ranging between 500N and 800N, the number of specimens with crack formation under 800N was calculated as a percentage of the total number of specimens (Total N = 10). The following observations were noted:



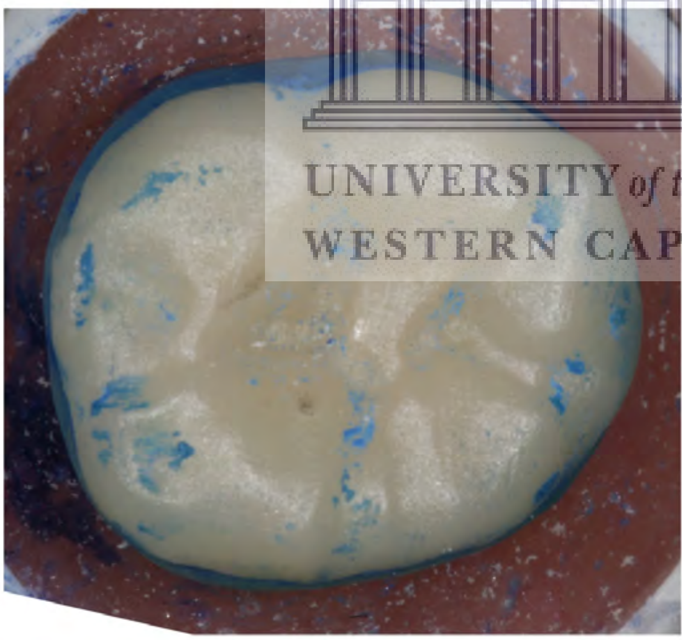
a) specimen from group A 0.8mm showing initial crack at 800N.



b) specimen from group A 1.0 mm showing initial crack at 1000N.



c) specimen from group B 0.8mm showing initial crack at 1500N.



d) specimen from group B 1 mm showing no sign of crack formation at 2000N

Figure 22: Each specimen was evaluated for signs of crack formation at intermittent loading values.

(a-d) show the cracks noted for each group and subgroup and the load value at which the crack was noted.

Group A: Class I cavity with composite core

In the porcelain thickness of 0.8mm 60% of the specimens showed signs of fracture of the porcelain when 800N force was applied. In the porcelain thickness 1mm, the number of cracked specimens decreased, with 20% of specimens showing signs of crack formation at values under 800N. (Table 9

Table 9: Group A: Load value of initial crack formation as a percentage of number of specimens.

Group	THICKNESS	500N	800N	1000N	1200N	1500N	1700N	2000N
A	**1.0**		20%	30%	40%	10%		
	Under 800N		**20%**					
	0.8	20%	40%	30%	10%			
	Under 800N		**60%**					

Group B: Class I cavity with no composite core

In the porcelain thickness of 0.8mm, only 10% of the specimens showed any crack formation at values under 800N. In the porcelain thickness of 1.0mm, no specimens showed signs of crack formation at values under 800N (see Table 10).

Table 10: Group B: Load value of initial crack formation as a percentage of the number of specimens

Group	THICKNESS	500N	800N	1000N	1200N	1500N	1700N	2000N
B	**1.0**			30%	10%	10%		50%
	Under 800N		**0**					
	0.8		10%	20%		20%	30%	20%
	Under 800N		**10%**					

It is important to note that in three cases, the initial cracks' load values were higher than the final maximum load value (Table 11).

Table 11: Specimens that registered a maximum load value lower than the initial crack formation value.

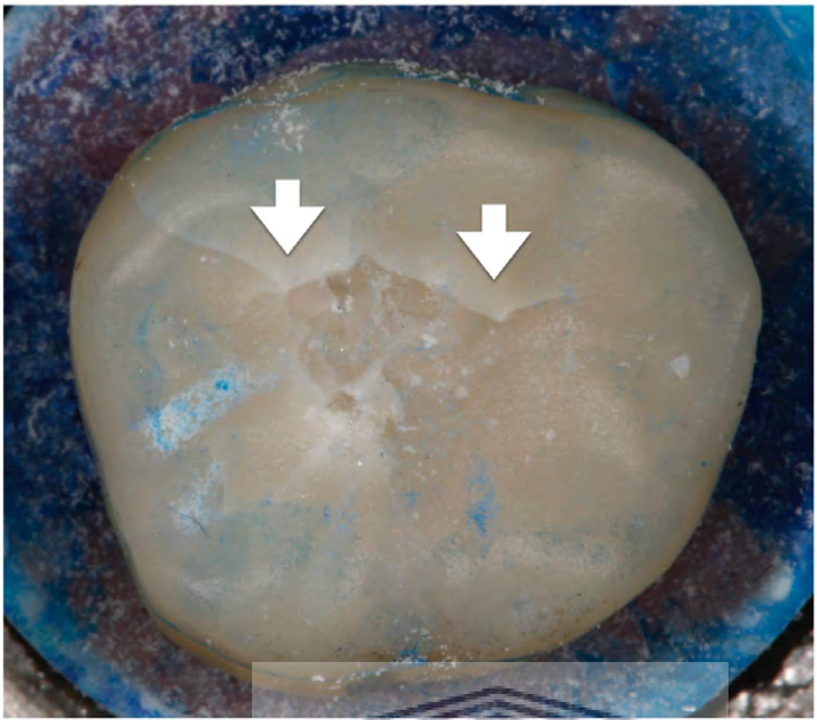
Specimen	Group	Thickness	Crack	Fracture
13	A	2	1000	380
14	A	2	500	492
37	B	2	1700	1540

1.14 Classification of mode of fracture

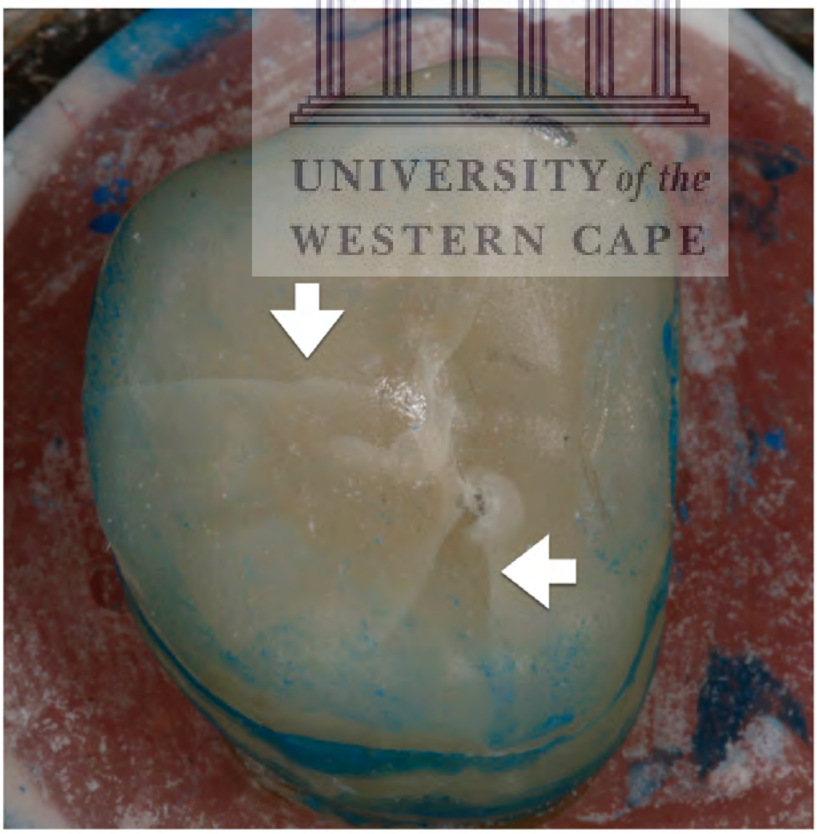
Following previous classification by Guess et al (Guess *et al.*, 2013), the final fracture patterns observed in this study were classified according to the following criteria:

I. Extensive crack formation within the ceramic;
II. Cohesive fracture within the ceramic;
III. Fracture within the ceramic and tooth structures;
IV. Ceramic and tooth fracture involving the root.

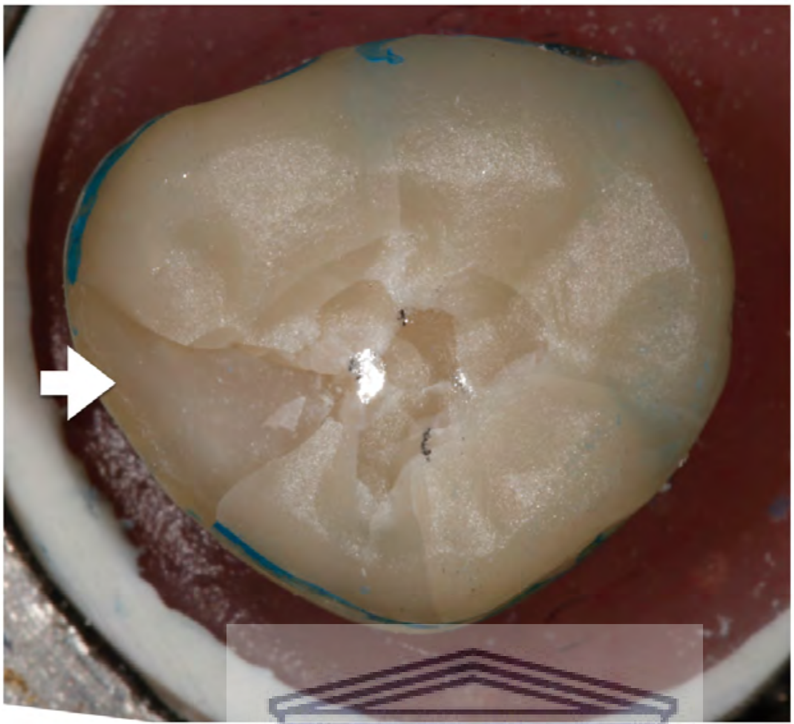
Fracture modes were further evaluated according to their restorability. All specimens with fractures that did not affect the underlying tooth structure (Groups I, II & III in classification) were deemed restorable. Specimens from group IV were classified as un-restorable(Guess *et al.*, 2014). All groups were shown as a percentage of the total number of specimens.



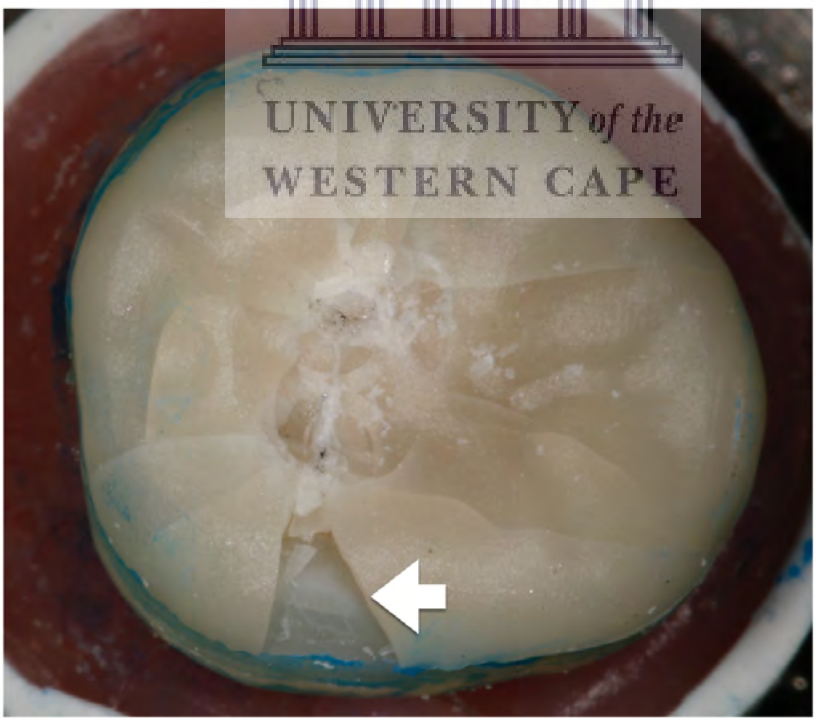
a) specimen with a Group I cohesive fracture of the ceramic



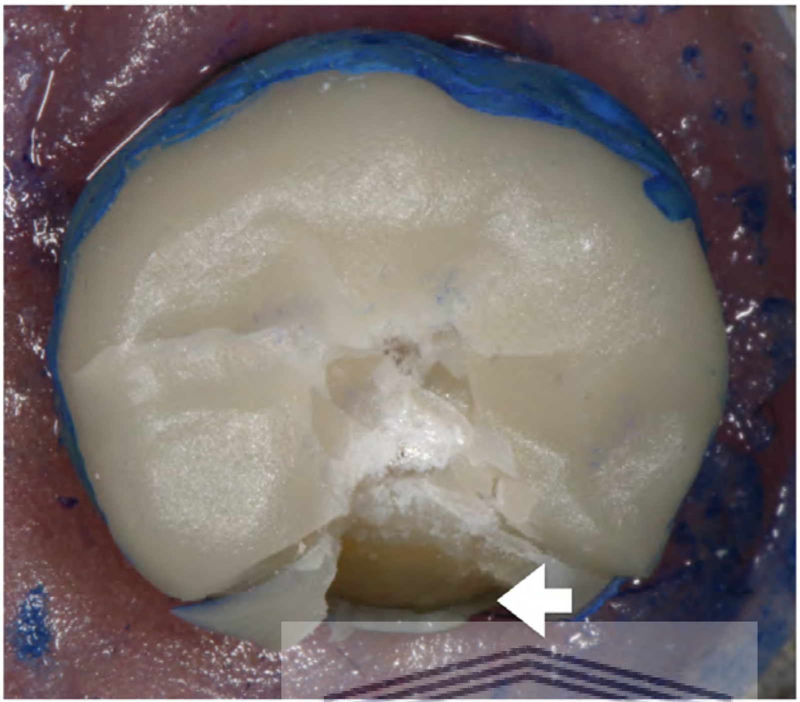
b) specimen with a Group I cohesive fracture of the ceramic



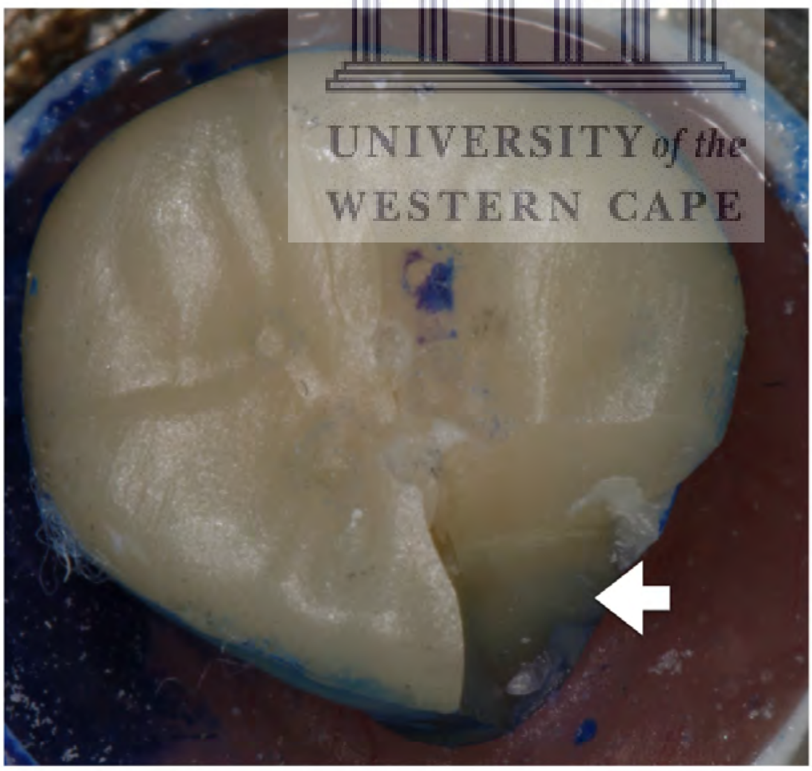
c) specimen with a Group II fracture of the ceramic that does not damage the tooth structure



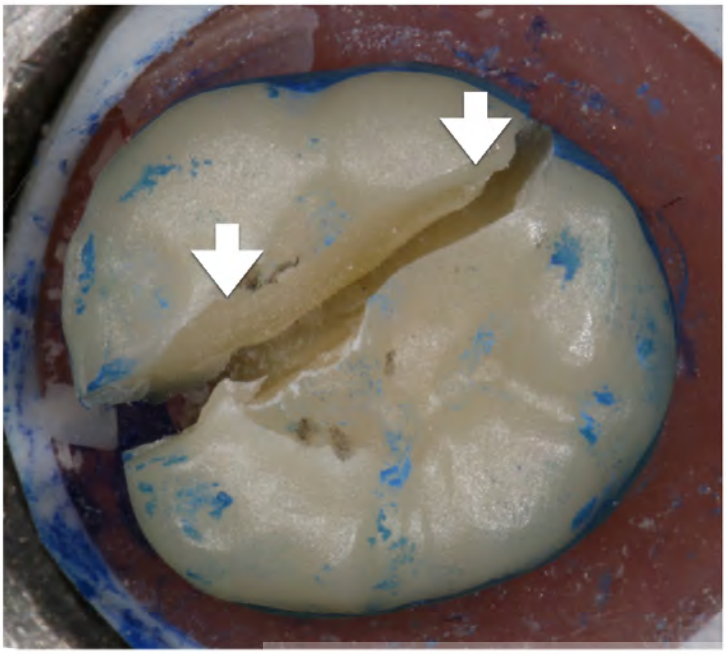
d) specimen with a Group II fracture of the ceramic that does not damage the tooth structure.



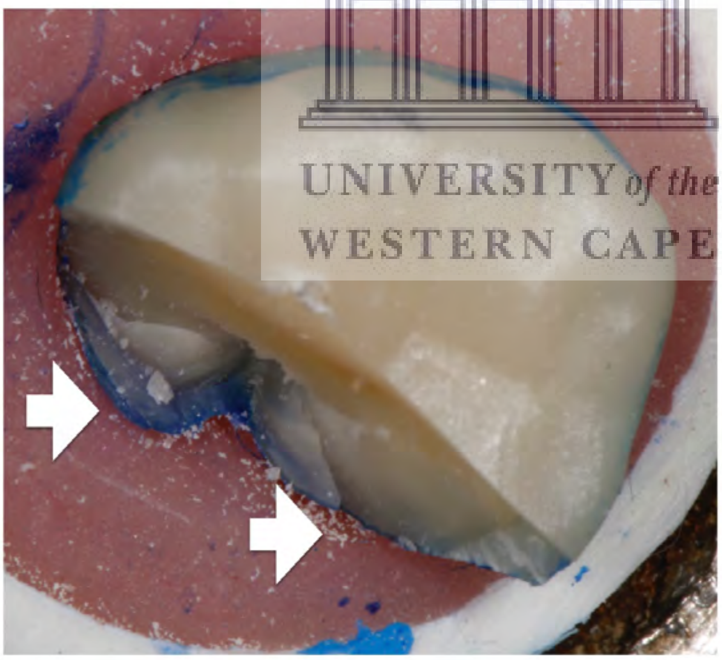
e) specimen with a Group III fracture that includes damage to the tooth structure



f) specimen with a Group III fracture that includes damage to the tooth structure



g) specimen with a Group IV fracture that includes damage to the root



h) specimen with a Group IV fracture that includes damage to the root

Figure 23: (a –h): Showing the different images of the fracture type found.

Fracture mode I (a and b). Fracture mode II (c and d). Fracture mode III (e and f). Fracture mode IV (g and h).

Group A

When evaluating the mode of fracture in the porcelain thickness 1mm, 60% of specimens had fractures limited to the restoration itself. An additional 30% were un-restorable.

In the porcelain thickness of 0.8mm, this increased to 80% of specimens with fractures limited to the restoration and only 20% were classified as un-restorable (Table 12).

Table 12: Group A - Classification of mode of fracture as a percentage of number of specimens.

Group	THICKNESS	I	II	III	IV
A	1.0	10%	50%	10%	30%
	0.8	40%	40%		20%

Group B

When evaluating the mode of fracture in the porcelain thickness 1.0mm, only 20% of specimens had fractures limited to the restoration itself. An additional 70% were un-restorable.

In the porcelain thickness of 0.8mm, the number of fractures limited to the ceramic increased to 30% of specimens, with an additional 60% being un-restorable (Table 13.)

Table 13: Group B: Classification of mode of fracture as a percentage of number of specimens.

Group	Thickness	I	II	III	IV
B	1.0	10%	10%	10%	70%
	0.8		30%	10%	60%

CHAPTER 5

Discussion

During this *in vitro* study, the ideal thickness of monolithic lithium disilicate restorations with various preparation designs were investigated. By evaluating two thicknesses of lithium disilicate with two distinct preparation designs, this study aimed to replicate the clinical situation clinicians could face when large areas of tooth structure have been lost through caries or erosion. When restoring such large areas, the clinician needs to decide on the ideal restorative thickness and technique that would best suit the clinical situation. Such an ideal thickness, or "Goldilocks" thickness of ceramic together with the ideal preparation design, would create a restoration that would withstand normal masticatory forces, but when exposed to extreme conditions, would only cause damage to the restoration, leaving the tooth structure unaffected.

When considering the "Goldilocks" thickness of the restorative and the ideal preparation design, the clinician needs to find a balance between the strength and durability of the restorative material and the strength and survival of the remaining tooth structure in the long term. Often, large amounts of healthy tooth structure are sacrificed to allow for enough restorative space to accommodate the inherent weakness of the restorative material (Dietschi & Spreafico, 2015). This sacrifice leads to a reduction in the strength of the remaining tooth, often leading to an increase in fractures that are difficult to repair, or fractures that are seen as catastrophic, leading to the loss of the tooth (Beier *et al*., 2012). Alternately, too thin a restoration will lead to a reduction of material strength with lower clinical survival rates and increased material complications (Krämer et al., 2005).

Cavity design optimization (CDO) was developed to help overcome some of the unnecessary tissue removal when creating inner-cavity designs for indirect restoratives (Jackson, 1999). Using such principals in a bio-substitutive manner (Dietschi & Spreafico, 2015), the clinician has the opportunity to maximise the strength of the restorative material while preserving the maximum amount of sound tooth structure.

Following such CDO or bio-substitutive cavity designs, current literature has investigated the ideal thickness of the restorative lithium disilicate as it is bonded to a partial resin substrate in the bio-substitutive model (Sasse et al. 2015). However, the author has not identified any research that has directly compared the use of such a bio-substitutive approach with a more traditional cavity design approach where no resin dentine-replacement is used.

To find the ideal balance and achieve the "Goldilocks" restoration, three fundamentals of minimally invasive dentistry and indirect porcelain restorations need to be considered:

- The material used for restoration
- The technique used for cementation
- The preparation design

The development of stronger particle-filled ceramics such as lithium disilicate with its strength and pleasing aesthetic properties have made these ceramics a popular restorative material in a minimally invasive protocol (Christensen, 2011). This inherent strength has a significant impact on the underlying preparation design with lithium discilicate being used more widely in a minimally invasive, partial restoration protocol (Silva *et al.*, 2012; Valenti, 2015; Rocca *et al.,* 2015).

The strength of the restorative material is also dependent on the ability to adhesively bond it to the underlying tooth structure. The use of adhesives such as "universal adhesives" incorporates the versatility of being adaptable to the clinical situation, producing excellent immediate bond strength to various bonding substrates (Wagner et al., 2014). The resin cements in turn forms a chemical bond with the adhesive, thereby generating a particularly strong bond between the tooth structure and the ceramic. Such bond increases the fracture resistance and thus the survival rate of all-ceramic restorations. Minimally invasive restorative techniques, such as non-retentive occlusal veneers, would be unthinkable without adhesive luting composites (Vargas et al., 2011).

By incorporating these popular adhesive materials and ceramics, the conservative preparation design for this study uses the CDO and a bio-substitutive approach which is based on preparation designs of similar studies by Clausen *et al*. (2010) and Sasse *et al.* (2015). A conservative preparation design with straight bevelled finish lines with soft internal angles and standardized inter cusp angle was used (Arnetzl & Arnetzl, 2009). This is supported by Clausen *et al*. (2010) who showed that marginal preparation design had no significant influence on fracture resistance. In addition, in this study a single large defect was created in the occlusal aspect of the tooth to simulate the clinical situation where large amounts of tooth structure had been lost (Figure 24 shows a clinical situation where such a defect is present).

1.15 Fracture values

Having randomly divided forty molar teeth into two groups (A and B), each group received occlusal cavity preparations simulating a Class I defect (Figure 18; a - d) to simulate clinical conditions. The specimens of group A had the Class I defect adhesively filled using direct composite material to create a conservative and uncomplicated preparation design (Figure 18; e - f). This follows the Cavity Design Optimization (CDO) principals as stated by Dietschi *et al*. (2015). In a similar study using similar preparation designs, Sasse *et al*. (2015) results suggested that this type of preparation protocol, where adhesive composite material using

CDO techniques is used, had only minor influence on the fracture resistance of the restorative ceramic.

Each group was further divided into two subgroups, each with a distinct ceramic thickness (0.7mm in the fissure and 1mm over the cusp or 0.5mm in the fissure and 0.8mm over the cusp). After static loading using a universal testing machine (Zwick Z010/TN2A, Ulm, Germany) the maximum fracture loads were evaluated. The porcelain thicknesses of 0.7 - 1mm in group A (composite core preparation) with a mean fracture values noted as 2460 Newton, were similar reported by Sasse *et al* (2015) under similar test parameters. In this current study, there was a significant difference in the maximum fracture value between the restorative thicknesses of 0.7 - 1mm and 0.5 - 0.8mm ($p < 0.05$, Kruskal-Wallis test) of Group A. This corresponds with Sasse's results which also showed similarly significant reduction in fracture values of ceramics thinner than 0.7 – 1mm when using a composite core. Our finding therefore supports the conclusion by Sasse that a minimum thickness of 0.7–1.0 mm should be maintained when a self-etching primer is used for conditioning of the tooth substrate in an occlusal veneer design restoration using lithium disilicate and CDO principals (Sasse *et al*., 2015).

The similarities between the results of the current study and those of Sasse (2015) allow us to deduce that, had the current study investigated the clinical situation where no Class I defect was present and dentine remained similar to a dental erosion lesion, the dentine core preparation would have achieved similar results to that of the composite core (with the same design). This is in accordance with the conclusions that were made by Sasse in 2015.

In addition to the preparation design in Group A (composite core preparation) this study investigated the clinical decision where CDO principals were not used, and all missing structure was replaced with ceramic only (Group B – Ceramic core. Figure 18; g - h). Such a preparation design would create ceramics with far greater thicknesses in the fissure area leaving them potentially more resilient to fracture.

When evaluating the maximum fracture values of two similar thicknesses of ceramic (1mm over the cusp and 1.7mm in the fissure or 0.8mm over the cusp and 1.5mm in the fissure) in group B (no composite core preparation) there was no significant difference noted in their fracture values ($p < 0.05$, Kruskal-Wallis test). This can be attributed to the thicker porcelain in the fissure area, that is now being filled by the ceramic (Figure 19; e – f), leading to more resilient restorations even when preparations over the cusps were reduced.

Similarly, due to the far greater thicknesses of the ceramic in the fissure area, it could be expected that the resultant restorations would produce significantly higher fracture values than that of group A. However, the current study results showed that when comparing the fracture values of the 1mm thick porcelain restoration of the two different preparation designs (Group A - 2460 Newton and Group B - 3142 Newton, refer to Table 12), no statistical significance was noted in the maximum fracture resistance ($p > 0.05$, Kruskal-Wallis test). When evaluating the fracture values of the thinner porcelain restoration of the two different preparation designs of Group A and B, a statistical significance was noted in the maximum fracture resistance ($p < 0.05$, Kruskal-Wallis test).

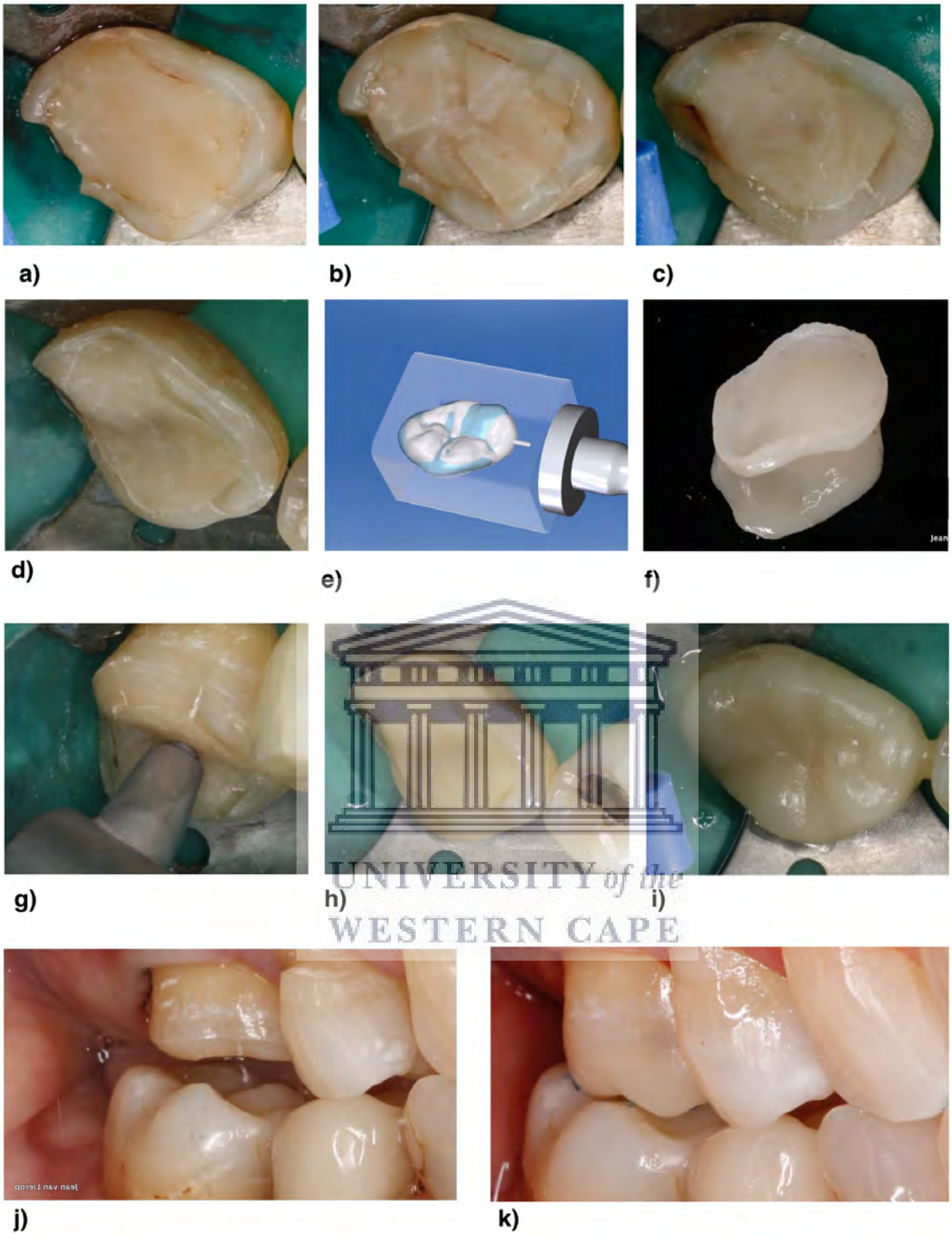
It can therefore be concluded that when using restorations of a thickness of 1mm over the cusp, the use of composite core or ceramic core would result in similar load performances. Should the ceramic be reduced over the cusp area, a ceramic core would result in higher maximum fracture values.

When using these *in vitro* results and conclusions to guide the clinical situation, one should take into consideration the bite forces experienced during mastication. As can be seen in figure 14 the results of numerous laboratory experiments that investigated the maximum bite force vary. This is due to several factors that include: subject gender and age, food type, jaw disorders, tooth quality, muscular strength, and other factors (Osborn, 1996). This reported maximum bite force generally falls within the range of 500-800 N. These maximum masticatory forces that exist during function and maximum load, contribute greatly to the fatiguing of both the restoration and remaining tooth structure. When evaluating the performance of minimally invasive lithium disilicate restorations, these maximum masticatory forces should be considered. Such values can give a better indication of the potential long-term clinical performance of the restoration and remaining tooth.

In an attempt to evaluate the impact of clinically relevant masticatory forces on the fracture resistance of the varies restoration designs, each specimen was investigated for any signs of damage at varying load intervals during the loading protocol. These load values were recorded at intervals of 500N, 800N, 1000N, 1200N, 1500N, 1700N, 2000N before maximum load was applied. All specimens that showed initial crack formation under 800 Newton were grouped together. These specimens could be seen as being at higher risk of failure under clinical load.

The resultant values indicated that in Group A (composite core), the porcelain thickness of 0.7 - 1mm had only 20% of specimens showing signs of crack formation at values under 800N. In the porcelain thickness of 0.5 - 0.8mm this increased to 60%. This could have the clinical significance that, when using a preparation design that incorporates CDO preparation techniques, porcelains thinner than 0.7 – 1mm run a higher risk of failure under clinical load. This conclusion correlates with Sasses' (2015) findings during dynamic load testing using a masticatory simulator. Here they found that only the restorations with a thickness of 0.7–1mm withstood dynamic loading unharmed. Restorations with thinner porcelain thicknesses showed increased failure under dynamic loading. Both the findings of this study and that of Sasse, support the clinical use of ceramic thickness of 1– 0.7mm when CDO techniques, in a bio-substitutive model, are used. A prediction on the remaining longevity of the restorations already showing crack formation cannot be made since no studies on this subject have been published so far.

The values of initial crack formation in Group B (ceramic core) were significantly higher than that of group A. Porcelain thicknesses of 1mm over the cusp showed no signs of crack formation at values under 800N and 50% of restorations withstood forces over 2000N. Only 10% of porcelain at thickness of 0.8mm over the cusp showed any crack formation under 800N, with 20% surviving loads of over 2000N. This supports the assumption that the thicker ceramic in the fissure area increased the strength of the ceramic creating a clinically resilient restoration.

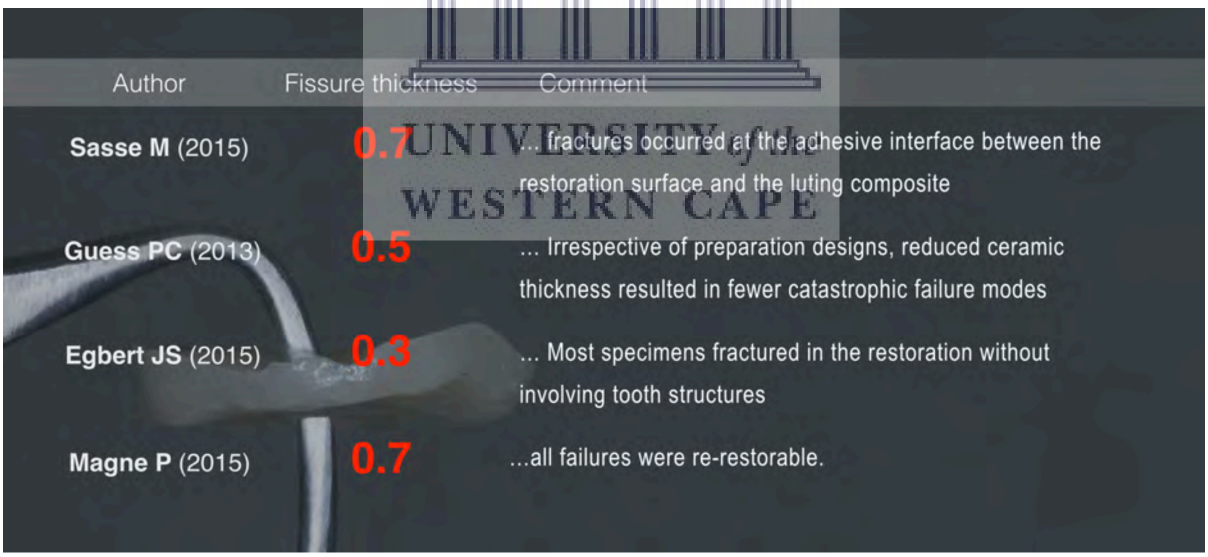


(a - d) preparation; **(e - f)** manufacture of CAD/CAM lithium discilicate; **(g - i)** cleaning of tooth surface, application of bonding agent and cementation of restoration;
(j) - confirmation of volume of reduction to allow for a clinical sound restoration;
(k) - final result

Figure 24: Clinical situation where a reduced thickness lithium disilicate overlay was used. (Dr Jean van Lierop)

1.16 The type of fracture

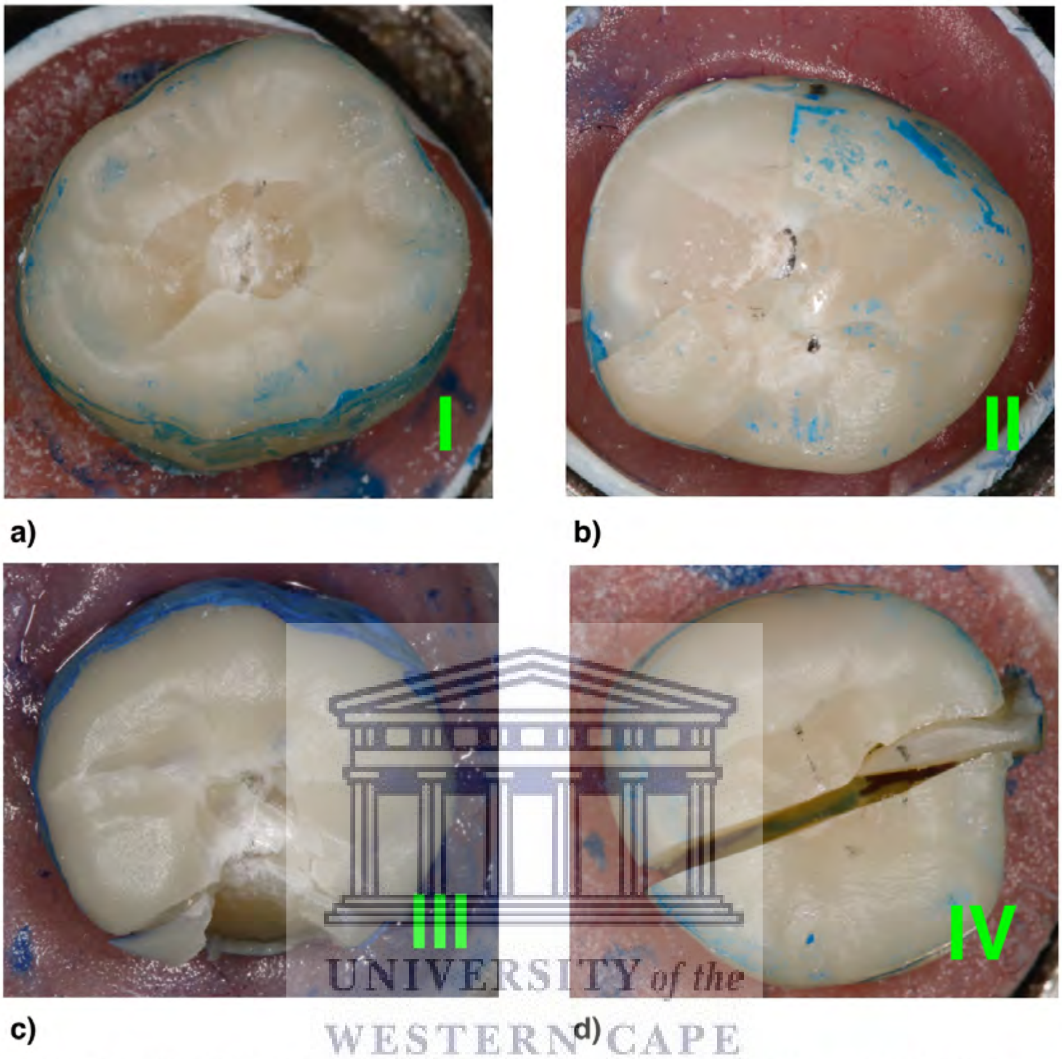
When final fracture of the thin occlusal veneer restoration does occur, the type of fracture takes place is of great clinical importance. In recent studies, focus has been given to determining the mode of fracture and its impact on the restorability of the underlying tooth structure once fracture has occurred. It has been shown that thicker restoration show more catastrophic fractures with extensive damage to the underlying tooth strucre structure that is unrestorable, whereas thinner restorations generally show less damage to the underlying tooth (Guess *et al.*, 2013; Egbert *et al.*, 2015; Magne *et al.*, 2015; Sasse *et al.*, 2015a). This has a direct influence on the restorability and long term prognosis of the tooth. Image Figure 22 gives an indication of the results of some of these studies and their conclusions.



Author	Fissure thickness	Comment
Sasse M (2015)	0.7	... fractures occurred at the adhesive interface between the restoration surface and the luting composite
Guess PC (2013)	0.5	... Irrespective of preparation designs, reduced ceramic thickness resulted in fewer catastrophic failure modes
Egbert JS (2015)	0.3	... Most specimens fractured in the restoration without involving tooth structures
Magne P (2015)	0.7	...all failures were re-restorable.

Figure 25: The mode of restoration failure at various fissure thicknesses as noted in current studies

In the current study, considering the increased resilience to fracture of the thicker restorations of Group B, the current study also investigated the mode of failure that occurred. This is relevant from a clinical perspective, where the ability to restore the failed restoration would be based on the complexity of the fracture that occurred (Figure 26 gives an overview of the fracture mode classification used). Where failure modes are limited to the ceramic, renewing the restoration could readily reverse the restoration failures (Groups I & II). In contrast, failures involving the underlying tooth structure (Group III) would require further, more complex treatment, including the possibility of endodontic treatment. In some instances, catastrophic failure (Group IV), would lead to the loss of the tooth. This highlights the advantage of preparation techniques that allow for minimally invasive strategies that preserve the natural tooth structure, leaving a stronger remaining tooth and increasing its lifespan.



a- d) classification of type of fracture: **I** - extensive crack formation within ceramic; **II** - cohesive fracture within ceramic; **III** - fracture within ceramic and tooth stricture; **IV** - ceramic and tooth structure fracture involving the root

Figure 26: Simplified classification of mode of fracture

In the current study, 70% of specimens in Group A, with the porcelain thickness 0.7 - 1mm, showed modes of fracture limited to the restoration itself. These were all restorable. In addition, 30% were un-restorable. For the thinner restorations in the same group, 80% of specimens showed fractures limited to the restoration and only 20% were classified as un-restorable (table 23). These values change drastically when one looks at the modes of failure of Group B (ceramic core). Here only 20% of specimens had fractures limited to the restoration itself and an additional 70% were un-restorable. This improved marginally for the thinner porcelain thickness (0.5 - 0.8mm with ceramic core) to 30% of specimens showing fractures limited to the restoration and 60% having damage that cannot be restored (Table 23).

This drastic increase in the number of catastrophic failures found with the all-ceramic restoration correlates with previous studies that showed an increase in complex failures when larger volumes of tooth structure had been lost (Magne & Belser, 2003; St-Georges *et al*., 2003). Such fractures have significant clinical implications, with the complete loss of the tooth being inevitable for most of these restorations.

The goal of this study was to identify the ideal porcelain thickness and preparation design that would create a clinically acceptable restorative while maintaining strong remaining tooth structure. This goldilocks thickness of ceramic and underlying preparation design, would create a restoration where clinically relevant masticatory forces do not cause damage, but under extreme conditions, the restoration would be the first point of failure. This would leave the tooth structure mostly intact and contribute to the longevity of the underlying tooth.

It is therefore important to consider what the clinically relevant strength should be. When one considers the maximum fracture resistance of unprepared natural posterior teeth to be reported at 2680N, then it is clear that maximum loads of similar values would be more than acceptable. When fracture values higher than that of the natural tooth is found, one would deduce that far greater damage would occur to the tooth structure under extreme load. This is simply due to the fact that the weaker of the two structures would fail first under load. As the restoration is often stronger than the underlying tooth structure, the tooth would be the point of failure, leading to catastrophic consequences. In addition, if the restoration shows lower maximum load values, the reduced strength of the restoration would lead to failure of the restoration itself before damage to the underlying tooth structure takes place. This would more than likely leave the tooth repairable.

Of further clinical consideration is the fatigue resistance of the restoration and preparation design. When one takes into consideration the maximum masticatory forces of 500 – 800 N, then restorations that show no signs of initial crack formation or damage at values under 800N should result in clinically lower fatigue failures. Although such an assumption should be made with caution, direct correlation could be drawn between this study's results and that of similar studies that investigated fatigue resistance.

In Group A, the mean maximum load value is recorded at 2460N for 0.7 – 1mm thick ceramic. In this group, only 30% of specimens showed catastrophic failure. In addition more than 80% of the restorations did not show signs of damage at functional loads under 800N. This is in direct contrast with the same thickness restoration of Group B (ceramic core). Here, mean maximum loads were greater (3142 N) with the resultant number of catastrophic failure being far more.

When one applies the "Goldilocks" principal of ceramic, (where a restoration is created that survives normal masticatory function, but under extreme conditions, leaves the tooth structure intact) it can be deduced that the use of a ceramic core would create a theoretically stronger restoration, but, under extreme load, could lead to more significant damage to the remaining tooth structure. When composite is used in CDO technique, a restoration thickness of 0.7 – 1mm is of similar strength than that of a restoration with a ceramic core, but the number of catastrophic failures is greatly reduced. This would lead to the conclusion that where large volumes of dentine have been lost, a composite core and CDO with a lithium disilicate restoration at thickness of 0.7 - 1mm would give the ideal balance between restorative strength and strength of the remaining tooth structure. This would lead to better long-term survival of the tooth.

CHAPTER 6

Conclusion

Within the limitations of this *in vitro* study, it was concluded that:

1. The fracture resistance of monolithic lithium disilicate with a thickness of 0.7mm in the fissure and 1mm over the cusp, is significantly higher in fracture resistance than the thinner restorations of 0.5mm in the fissure and 0.8mm over the cusp. This can therefore be recommended as a minimum thickness of occlusal veneer designs when using adhesive cementation with a universal adhesive and selective etching.
2. With restoration thicknesses of 1mm over the cusp, the preparation design does not have a significant influence on the maximum fracture strength.
3. When evaluating the mode of failure of restorations and remaining tooth, restorative designs that make use of cavity design optimisation (CDO) principals using direct composite restorations, show less complicated fractures and may contribute to the longevity of the underlying tooth.
4. When using ceramic to restore defects where large volumes of dentine has been lost, a lithium disilicate restoration with thickness of 0.7–1.0 mm in combination with the use of cavity design optimisation (CDO) and adhesive cementation with a universal adhesive and selective etching, can be recommended for use.

CHAPTER 7

Limitations

- This is an *in vitro* study and may have limitations when translated to the clinical situation.
- This study used static loading and not dynamic loading, as may be the case in the oral environment.
- Factors in the mouth, such as the impact of musculature, the patient's chewing patterns and occlusion, may all impact on fracture pattern.
- Only one porcelain material was tested in this study. Further investigation is needed on the use of other materials that could show similar results.
- Further clinical trials are required to correlate these *in vitro* results.

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APPENDIX 1

UNIVERSITY of the WESTERN CAPE

Oral & Dental Research Institute
Faculty of Dentistry and WHO Oral Health Collaborating Centre
University of the Western Cape
Cape Town

Patient Information Sheet to be given to the patient to take home

I, Dr Jean van Lierop am a qualified dentist involved in research and training at the University of the Western Cape, Faculty of Dentistry.

I am doing research on porcelain restorations.

After the removal of your teeth, they are either discarded or given to the students to practice on. I wish to use your teeth to be able to determine the ideal thickness and strength of porcelain restorations.

Donating your teeth in the study is on a voluntary basis. Donating your teeth for this study or refusing to participate will not harm or prejudice you in any way. The teeth supplied to me will not have your name on it as well as I will not be able to identify you in any way. Upon completion of this study the teeth will be discarded.

Participating in the study will definitely benefit future studies and will add to our existing pool of knowledge. All information will be kept strictly confidential.

Thanking you.

Dr Jean van Lierop
Researcher
Oral & Dental Research Institute
Oral Health Centre Tygerberg
Contact details: Tel: (021) 937 3090
Mobile: 072 220 3718

If you have any other queries, you are welcome to contact the head of the research institute, Dr D. Moodley at 021 937 3090

I, (Patient name)..., fully understand the information supplied to me by Dr Jean van Lierop in this information sheet

Signature: ....

Date: ....

APPENDIX 2

UNIVERSITY OF THE WESTERN CAPE/PGWC

FACULTY OF DENTISTRY

PATIENT CONSENT TO USE EXTRACTED TEETH

Surname:	Date of Birth:
Name:	File No:

I,.. hereby give consent to use my/my child's extracted teeth. I understand that the teeth concerned have no diagnostic value and would normally be discarded. I understand that the teeth will be anonymous at the point of collection and completely unidentifiable in the laboratory, therefore my consent cannot be withdrawn as the teeth cannot be traced back to me. I have been informed that the teeth may be stored for as long as needed in a secure environment. When discarded, they will be discarded according to Department of Health protocols.

I hereby give consent for my extracted teeth to be used for education, teaching, training and approved research purposes. The research performed may be any type of unspecified research, but DNA will not be used and any extracted cells/tissue will not be immortalized to create cell lines. I understand that my consent or refusal will in no way affect my /my child's dental care.

Patient Signature: .... Date:..

Parent/Guardian (if patient under 18 years) Name: ....

Signature... Date: ……..

Child assent (7-17 years): ………..……… Date: …………….........................

Witness Name & Signature.............................. Date: ……………….....................

Prepared by Dr Jean van Lierop (June 2016)