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To curiosity and the courage to follow your own path

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ABSTRACT

This series of *in vitro* studies consists of four studies, which aimed to deepen knowledge of variables that may affect the load-bearing capacity of a restored tooth, particularly from the perspective of a worn tooth. It was investigated how material selection, cavity design, bonding of the restoration, thickness of the occlusal veneer and cement layer, and water storage influence the fracture load of a restored tooth. The indirect restorative materials used were hybrid ceramic (HC) and lithium-disilicate glass ceramic (LDGC). Furthermore, direct particulate-filled resin composites (PFC) and short-fiber-reinforced composite (SFRC) occlusal veneers were studied.

The results showed that material selection significantly affected the fracture load of a restored tooth. In general, LDGC was considered favorable compared with HC regarding fracture load. However, HC recorded higher fracture load when used as a thin (0.5 mm) occlusal veneer with a 200 µm thick cement layer. Regarding cavity design, a rounded margin MOD cavity recorded slightly higher fracture load compared with an edge-shaped design. Chamfer preparation, however, had no impact on the fracture load of teeth restored with occlusal veneers. In bonded restorations, tooth fractures occurred, whereas in non-bonded teeth, restorations mainly loosened without tooth fractures. Teeth restored with SFRC occlusal veneers exhibited enhanced fracture load and a more favorable fracture type compared with teeth restored with PFC occlusal veneers. Six months of water storage did not influence the fracture load of teeth restored with direct occlusal veneers in this study setup.

It can be concluded that the type of material needs to be carefully considered when restoring a tooth. The studied variables affected the behavior of restored teeth under loading. From the fracture load perspective, minimally invasive methods may be applicable for occlusal restorations in molars.

KEYWORDS: Occlusal veneer, Worn tooth, Lithium-disilicate glass ceramic, Hybrid ceramic, Resin composite, Fiber-reinforced composite

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TIIVISTELMÄ

Tämä *in vitro* -tutkimussarja koostuu neljästä osatyöstä, joiden tavoitteina oli syventää tietoa muuttujista, jotka saattavat vaikuttaa paikatun hampaan kuormankantokykyyn erityisesti kuluneen hampaan kannalta. Tutkittiin, kuinka materiaalivalinta, kaviteetin muoto, täytteen sidostuminen, okklusaalisen laminaatin ja sementtikerroksen paksuus sekä hampaiden vesisäilytys vaikuttivat paikatun hampaan murtokuormaan. Tässä tutkimuksessa epäsuorina paikkamateriaaleina tutkittiin hybridikeraamia (HC) ja litiumdisilikaatti-lasikeraamia (LDGC). Lisäksi suoran tekniikan materiaaleista tutkittiin hiukkaslujitettuja komposiitteja (PFC) sekä katkokuitukomposiittia (SFRC).

Tulosten mukaan materiaalivalinnalla oli huomattava vaikutus paikatun hampaan murtokuormaan. Yleisesti ottaen LDGC saattaa olla suotuisampi murtokuorman kannalta kuin HC, mutta havaittiin, että 0,5 mm ohuilla HC-täytteillä paikatuilla hampailla saavutettiin suurempi murtokuorma, kun sementtikerroksen paksuus oli 200 µm. Mitä tulee kaviteetin muotoon, pyöristetty MOD-kaviteetin muoto oli hieman suotuisampi murtokuorman kannalta kuin teräväkulmainen MOD-kaviteetti. Kaarroshionnalla ei ollut kuitenkaan vaikutusta okklusaalisella laminaatilla paikatun hampaan murtokuormaan. Sidostetuissa täytteissä havaittiin hammaskudoksen murtuma, kun taas sidostamattomissa täytteissä täyte irtosi hammaskudoksesta ja hammas säilyi ehjänä. Hampaissa, jotka paikattiin katkokuitulujitteisella komposiitilla, havaittiin suurempi murtokuorma ja suotuisampi murtumistyyppi verrattuna hampaisiin, jotka paikattiin hiukkaslujitetulla komposiitilla. Kuuden kuukauden vesisäilytys ei vaikuttanut suoralla tekniikalla paikattujen hampaiden murtokuormaan tässä tutkimusasetelmassa.

Johtopäätöksenä materiaalin tyyppi täytyy ottaa huomioon hampaan paikkauksessa. Tutkitut muuttujat vaikuttivat paikattujen hampaiden käyttäytymiseen rasituksen alla. Murtokuorman kannalta minimaaliset invasiiviset paikkaustekniikat saattavat olla soveltuvia molaarihampaiden purupinnoille.

AVAINSANAT: Okklusaalinen laminaatti, Kulunut hammas, Litiumdisilikaatti-lasikeraami, Hybridikeraami, Resiinikomposiitti, Kuitulujitteinen komposiitti

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Abbreviations

ANOVA	Analysis of variance
BisGMA	bisphenol-A-glycidyl methacrylate
CAD/CAM	Computer-aided design and computer-aided manufacturing
CEJ	Cementoenamel junction
FEA	Finite element analysis
GPa	Gigapascal
HC	Hybrid ceramic
kN	Kilonewton
LDGC	Lithium-disilicate glass ceramic
mm	Millimeter
MOD	Mesio-occlusal-distal
MPa	Megapascal
µCT	Micro-computed tomography
µm	Micrometer
µTBS	Micro-tensile bond strength
N	Newton
nm	Nanometer
PFC	Particulate-filled composite
PMMA	poly(methyl methacrylate)
s	Second
SFRC	Short-fiber-reinforced composite
SEM	Scanning electron microscopy
TEGDMA	Triethylene glycol dimethylacrylate
UDMA	Urethane dimethacrylate
Wt%	Percentage by weight

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I Yli-Urpo, T., Lassila, L., Vallittu, P., Närhi, T., 2024. Co-Influence of Restoration Bonding and Inlay Cavity Design on Fracture Load of Restored Tooth. *European Journal of Prosthodontics and Restorative Dentistry*, 32, 1-8.

II Yli-Urpo, T., Lassila, L., Närhi, T., Vallittu, P., 2025. Occlusal Veneers and Load-Bearing Capacity of a Restored Tooth. *The International Journal of Prosthodontics*, 25, 206-213.

III Yli-Urpo, T., Lassila, L., Närhi, T., Vallittu, P., 2025. Cement layer thickness and load-bearing capacity of tooth restored with lithium-disilicate glass ceramic and hybrid ceramic occlusal veneers. *Dental Materials*, 41, 212-219.

IV Yli-Urpo, T., Määttä, J., Suominen, A., Vallittu, P. K., Närhi, T., Le Bell-Rönnlöf, A., Bijelic-Donova, J. Fracture load and three-dimensional internal void analysis of direct composites used to restore worn molars. Manuscript.

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1 Introduction

Occlusal wear of a tooth is a common condition that can compromise both aesthetics and function. As tooth wear becomes more prevalent, knowledge of different restorative techniques is essential for achieving long-lasting posterior occlusal restorations. Differences in mechanical properties between direct and indirect materials have been widely studied, but there is not an established method to restore a posterior tooth with minimally invasive occlusal restorations.

Traditionally, retentive restorations such as full-coverage crowns have been used to treat posterior teeth. However, the development of dental materials has enabled clinicians to utilize a wide variety of dental materials and minimally invasive restorative techniques, although retention is often needed (Cardoso et al., 2023). The popularity of computer-aided design and computer-aided manufacturing (CAD/CAM) techniques for indirect restorations has been increasing, allowing rapid manufacturing of indirect resin composite and ceramic restorations. However, there is a lack of knowledge regarding the utilization of novel direct and indirect dental materials for posterior occlusal restorations. Indirect restorations were examined in studies I, II and III of this thesis focusing on inlays (Study I) and occlusal veneers (Studies II, III). Besides indirect restorations, the mechanical properties of direct resin composite occlusal veneers may be sufficient for the posterior region (Josic et al., 2023), which were studied in Study IV of this thesis.

Material selection could be associated with the bonding of the restoration to enamel and dentin, affecting stress distribution within the restored tooth structure, and furthermore, the load-bearing capacity of a restored tooth. It is essential to gather information about the mechanical performance of restored teeth, which is determined by several factors, including the type of material, bonding of the restoration, cavity design, and thickness of the restorative structure. There is a lack of knowledge regarding these factors, particularly as novel adhesive technique allows the use of minimally invasive restorations.

Thus, the aim of this series of studies was to evaluate factors affecting the fracture load of occlusally restored teeth with varying direct and indirect restorative materials.

2 Review of the Literature

2.1 Occlusal Tooth Wear

Occlusal wear of a tooth is a common clinical finding, and its prevalence tends to increase with aging as natural teeth are preserved (Van’t Spijker A et al., 2009). Tooth wear has been classified as either physiological or pathological. During a lifetime, physiological changes in teeth may occur, including a reduction in enamel thickness and dentin sclerosis (Carvalho and Lussi, 2017). Occlusal tooth wear can occur due to erosion, attrition, and abrasion. Furthermore, parafunctional behavior, malocclusion, and endogenous acids may also contribute to occlusal wear (Leven and Ashley, 2023; Spijker et al., 2015), being more frequent in males than in females, possibly due to stronger masticatory forces (Schlenz et al., 2023). Dietary habits are also involved, as higher occlusal wear of first molars has been found in professional wine tasters compared with people not involved in wine tasting (Mulic et al., 2011). On the other hand, pathological tooth wear has been described as atypical tooth wear for the age of the patient, often involving pain, discomfort, or functional problems that may lead to further complications if untreated (Loomans et al. 2017). There is a lack of standardized criteria defining a pathological tooth wear. Signs and symptoms of a worn tooth include increased sensitivity, loss of vertical dimension of occlusion, esthetic problems (*e.g.* shortening of anterior tooth crown and yellow color), and temporomandibular disorders (Leven and Ashley, 2023). Preventative measures should always be the primary approach to managing tooth wear, and, if restorative procedures are needed, they should be as conservative as possible (Loomans et al., 2017). Prior to restorative treatment, the extent and progression of tooth wear and its etiological factors should be carefully identified, which might also influence restorative options and material selection (Loomans et al., 2017). Progressive wear or patient symptoms may indicate the need for restorative treatment, whereas in the absence of concerns or symptoms, a preventive approach should be prioritized (Loomans et al., 2017).

2.2 Restorative Options for Damaged Tooth

2.2.1 Direct Restorations

When damaged teeth are restored with direct restorations, a minimally invasive technique should always be considered, removing only carious tissue (Giacaman et al., 2018). Direct restorations are applied to the pretreated surface of the prepared tooth and then cured. Direct resin composite might offer a durable solution for restoring worn anterior and posterior teeth (Mehta et al., 2012; Loomans et al., 2017). Despite being a conservative and cost-effective solution, direct restorations have demonstrated clinical performance comparable to indirect restorations in occlusally restored posterior teeth (Wolff et al., 2024). In a clinical study by Crins et al. (2021), severe tooth wear restored with direct composite restorations showed a higher survival rate than indirect restorations after a 3-year follow-up. Also, Pallesen and van Dijken (2015) reported that resin composites in Class II cavities presented adequate performance after 30 years in clinical service. However, one reported shortcoming of direct resin composites is the high stress in restored teeth due to polymerization shrinkage (Dejak and Młotkowski, 2015), while other common complications include secondary caries and restoration fractures (Tennert et al., 2024).

2.2.2 Indirect Restorations

CAD/CAM technique allow a rapid procedure to fabricate indirect restorations, in which a restoration is designed and milled from a material block according to a scanned tooth preparation. Compared with direct composite materials, indirect materials have presented higher mechanical properties and promising performance in restoring worn anterior and posterior teeth (Maier et al., 2024). However, due to their high mechanical properties, a concern with indirect materials is the potential wear of the antagonist tooth (Heintze et al., 2008; Mao et al., 2024). Although both direct and indirect restorations have presented promising performance in treating worn posterior teeth (Josic et al., 2023), indirect restorations may be indicated for large cavities, as polymerization shrinkage might be a concern with direct resin composite restorations (Veneziani, 2017). Furthermore, indirect restorations might be advantageous for restoring endodontically treated teeth in the long-term, although further research is needed (Shu et al., 2018). The main failure mechanisms of indirect composite restorations reportedly include secondary caries, fractures, and debonding (Josic et al., 2023). Indirect restorations have been classified according to tooth preparation design, including inlays, onlays, overlays, veneers, and crowns. In this thesis, inlays and occlusal veneers are further examined.

2.2.2.1 Inlays

Inlays are an option for restoring moderate tooth loss within the cusps of a tooth, when cuspal coverage is not required. Promising clinical performance has been found for both indirect and direct inlays (Angeletaki et al., 2016). For large posterior tooth defects, ceramic inlays might be an acceptable clinical solution (Galiatsatos et al., 2022), although both composite and ceramic inlays have demonstrated high survival rates clinically (Fron Chabouis et al., 2013; Morimoto et al., 2016). When it comes to cavity design, the highest stress concentration has been recorded in the internal angles of inlays, which can be reduced by rounded angles and well-bonded restorations (Couegnat et al., 2006). However, the significance of optimized cavity design has not yet been fully clarified. The minimal wall thickness of a mesio-occlusal-distal (MOD) cavity in molars prepared for adhesive CAD/CAM inlays has been proposed to be at least 1.5–2.0 millimeters (mm) (Ahlers et al., 2009).

2.2.2.2 Occlusal Veneers

Indirect restorative techniques may require more tooth preparation than direct restorations to achieve increased retention, although adhesive technology has enabled less-retentive preparations (Opdam et al., 2016). Minimally invasive techniques for indirect restorations have been developed. These include occlusal veneers, in which only the occlusal surface of a worn tooth is restored with preservation of dental tissue. Compared with crowns, occlusal veneers have shown increased fracture resistance of restored teeth, proposedly due to larger bonding area of crowns, in which tensile stresses were concentrated (Huang et al., 2020). Ceramic occlusal veneers have provided high survival rates in clinical studies, even as thin (0.4–1.3 mm) structures (Schlichting et al., 2022). Mechanical properties, especially fracture toughness, flexural strength, and elastic modulus, of materials are important when considering occlusal veneers, as resin-based materials allow the use of thinner occlusal veneers (Ladino et al., 2021). According to finite element analysis (FEA) and a laboratory study, 0.6 mm thin occlusal veneers made from resin composite dissipate more stress and exhibit higher fatigue resistance compared with lithium-disilicate glass ceramic (LDGC) counterparts, although both materials were considered functionally acceptable (Schlichting et al., 2011; Magne et al., 2012). Minimally invasive anterior and posterior indirect resin composite restorations for worn teeth have performed satisfactorily after 1 year (Crins et al., 2022) and 5.5 years in clinical service (Maier et al., 2024). When the performance of indirect resin composite and LDGC veneers was compared, both materials revealed adequate mechanical properties and performance for worn posterior teeth (Furtado De Mendonca et al., 2019; Maldonado et al., 2024).

2.3 Structure and Mechanical Properties of Direct and Indirect Restorative Materials

2.3.1 Direct Restorative Materials

2.3.1.1 Particulate-filled Composite

Particulate-filled composite (PFC) consists of an organic resin matrix and an inorganic filler particle phase bonded to the resin matrix via a silane coupling agent. The development of direct restorative materials has led from macrofilled to nanofilled composites (Ferracane, 2011). Along with hybrid resin composites, nanofilled composites ensure high polishability, improved wear resistance, and high strength (Alzraikat et al., 2018). Nanocomposites have also shown comparable clinical performance to hybrid composites and indirect resin composites, even in the posterior region (Alzraikat et al., 2018; Josic et al., 2023). In addition to filler particle size, filler loading and distribution, the morphology and composition of both the fillers and the resin matrix need to be considered when resin composites are compared (Kim et al., 2002; Sideridou et al., 2011; Randolph et al., 2016).

Filler loading (i.e. weight/volume fraction) is an important factor influencing the mechanical properties of resin composites (Kim et al., 2002). It could play an even more influential role in mechanical properties compared with filler size (Randolph et al., 2016). Filler shape has an influence on filler loading, as lower filler loading has been reported in resin composites containing irregular-shaped particles (Kim et al., 2002). Also, filler particles with sharp edges might work as a fracture initiation sites (Sabbagh et al., 2004; Beun et al., 2007). However, according to in silico multi-scale analysis, under similar filler volume content, composites with irregular-shaped filler particles exhibit higher flexural modulus compared with spherical fillers, possibly due to a higher filler surface area of irregular-shaped particles (Sakai et al., 2021). A higher elastic modulus of resin composite was observed with irregular-shaped particles in a surface nanoindentation test, perhaps due to less rearrangement of irregular-shaped particles compared with spherical filler particles during loading (Masouras et al., 2008). Regarding wear resistance, decreasing filler particle size and inter-particle distance improves the wear resistance of resin composite (Bayne et al., 1992).

Resin matrix composition influences the mechanical properties of resin composites. It has been reported that increasing urethane dimethacrylate (UDMA) content or replacing bisphenol-A-glycidyl methacrylate (BisGMA) with triethylene glycol dimethylacrylate (TEGDMA) in a resin mixture of UDMA, TEGDMA, and Bis-GMA, tensile and flexural strength of the resin matrix increased, but elastic modulus decreased (Asmussen and Peutzfeldt, 1998). Ilie (2021) also reported that besides the varying amount of filler loading and filler particle size, UDMA content in the resin matrix exhibited improved flexural strength, flexural modulus, and fracture toughness of resin composite. Filler particles also influence the strength of the resin matrix in resin composites. Monomers in the resin matrix bond to the surface of a filler particle, forming a layer of immobile monomers called the boundary layer. By increasing filler particle surface area within the resin composite by increasing filler loading and reducing particle size, the maximum number of monomers bound to filler particles is allowed to form boundary layers. The boundary layer is known to increase the elastic modulus of resin composite (Shen et al., 2020; Ilie, 2021). However, the shortcomings of conventional PFCs include low fracture toughness and polymerization shrinkage. According to Heintze et al. (2017), fracture toughness is the mechanical property that correlates best with the clinical success of restorations. The fracture toughness of PFC has been reported to be lower compared with that of dentin (Manhart et al., 2000), and therefore a PFC restoration can only partially restore the strength of the tooth.

2.3.1.2 Short-fiber-reinforced Composite

Instead of using particulate fillers, fiber fillers with a high aspect ratio can be incorporated into resin composites (Vallittu, 2014; Vallittu, 2018). Dental short fiber, *i.e.* discontinuous fiber-reinforced composite (SFRC) development began to a larger extent in the middle 2000s when positive effects of short glass fibers were demonstrated in numerous *in vitro* studies (Fennis et al., 2005; Garoushi et al., 2006a; Garoushi et al., 2006b; Garoushi et al. 2006c; Garoushi et al., 2006d; Garoushi et al., 2007). Since the introduction of SFRCs, significant development of the resin composite has taken place, and the resin composite of this kind is widely used in large composite restorations today (Obeid et al., 2025).

Resin composite containing randomly oriented short glass fiber fillers has improved fracture toughness to prevent catastrophic fractures (Lassila et al., 2018; Tsertsidou et al., 2023). SFRC presents crack-arresting mechanisms, including a longer crack path due to fiber pull-out and crack blunting, and fiber bridging arresting the crack path by decreasing stress at the crack tip (Alshabib et al., 2022). By improving fracture toughness, crack propagation through the material is impeded. Important factors for SFRC restorations are fiber aspect ratio, critical fiber length, fiber loading, and orientation of fibers, which might influence the performance of SFRC restorations. In addition, SFRC may have fiber alignment to take place in certain cavity sizes, and the isotropicity can turn to be anisotropicity in mechanical properties and polymerization shrinkage, as has been demonstrated with continuous fibers (Tezvergil et al. 2006). SFRC has been shown to positively influence the bonding of resin composite to the underlying substrate of dentin or other resin composite (Cekic-Nagas et al., 2008; Tezvergil et al., 2005; Tezvergil et al., 2007; Tezvergil et al., 2008; Tezvergil-Mutluay and Vallittu, 2014).

The maximum thickness of SFRC must be ensured for maximum work of fracture, covered by a thin PFC composite layer as instructed by the manufacturer (Tiu et al., 2021). Without PFC coverage, surface roughness and polishability may be concerns for SFRC restorations, although recent studies have exhibited promising findings of SFRC surface properties. It was reported that flowable SFRC containing microfibers exhibited similar surface roughness and bacterial adhesion compared to PFC materials after surface abrasion with 4000-grit abrasive paper (Lassila et al., 2024). Flowable SFRC has also demonstrated favorable wear characteristics compared with flowable bulk-fill resin composite (Lassila et al., 2019) and comparable wear to conventional PFC materials in a two-body wear test (Lassila et al., 2023). After analyzing surface properties of resin composites, Mangoush et al. (2021) reported that the incorporation of short fibers didn’t impair surface microhardness, roughness, wear depth, or gloss of an experimental fiber-reinforced CAD/CAM block. Furthermore, in a clinical evaluation, ElAziz et al. (2024) studied flowable SFRC restorations without proximal coverage in posterior teeth and concluded that uncovered SFRC restorations presented similar performance compared with PFC restorations in terms of secondary caries, proximal contact, anatomic contour, proximal texture, color match, marginal discoloration, and marginal integrity after an 18-month follow-up. However, more laboratory and clinical data are needed regarding the performance of SFRC restorations on the occlusal surface without PFC coverage.

2.3.2 Indirect Restorative Materials

2.3.2.1 Hybrid Ceramic

Indirect restorations are manufactured in a laboratory and cemented to the prepared tooth. Resin composite containing a high volume of filler particles and cured to a high degree of monomer conversion of the resin matrix has been described as hybrid ceramic (HC), as its mechanical properties resemble those of ceramic materials while retaining the advantages of resin composites, resulting in high flexural strength with lower abrasiveness and reduced brittleness (Goujat et al., 2018). Compared with direct resin composite, indirect resin composite presents an improved degree of monomer conversion, lower polymerization stress at the tooth-restoration interface, and higher mechanical properties (El-Damanhoury et al., 2021). Additionally, ideal anatomy, contours, and optimal contacts are easier to achieve with indirect restorations (El-Damanhoury et al., 2021). Corresponding to direct PFCs (section 2.3.1.1), filler particle size, loading, and composition may also influence the mechanical properties of indirect resin composites (Goujat et al., 2018; Lauvahutanon et al., 2014). However, the main reasons for failure of indirect HCs are debonding and fractures (Gresnigt et al., 2019), whereas direct restorations typically fail due to marginal leakage, secondary caries, and fractures (Shah et al., 2021; Demarco et al., 2023). In addition to variation in resin composite material, dentist-related and patient-related factors also affect the longevity of resin composite restorations (Demarco et al., 2023).

2.3.2.2 Glass Ceramic

Glass ceramics ensure good aesthetic properties and durability. In LDGC, lithium-disilicate crystals in a glassy matrix reinforce the glass ceramic. During the crystallization process, heat treatment transforms lithium-metasilicate crystals into reinforcing lithium-disilicate crystals, reaching the final strength of LDGC (Willard and Chu, 2018). Variations in chemical composition, microstructure, crystallinity, and mechanical properties occur among commercial LDGC materials (Lubauer et al., 2022). The commonly used LDGC IPS e.max CAD (Ivoclar Vivadent, Schaan, Liechtenstein) contains 70 vol% lithium-disilicate crystals measuring 5 micrometers (µm) in length and 0.8 µm in diameter (Willard and Chu, 2018).

All ceramics are brittle, although there are toughening mechanisms such as crack deflection around crystals, crack bowing, and crack trapping, which may depend on crystalline content, size, and aspect ratio (Lubauer et al., 2022; Liu et al., 2024; Serbena et al., 2015). Lithium-disilicate crystals form interlocking microstructures, which function as a strengthening mechanism for LDGC. It is noteworthy that residual stresses caused by differences in the thermal expansion coefficients of lithium-disilicate crystals and the glass matrix might influence the toughness of LDGC (Serbena et al., 2015). Li et al. (2016) studied micro-residual stress in LDGC and reported that the size of crystals is important for the strength of the LDGC material, as with decreasing crystal size, the interlocking effect is limited, while with increasing crystal size, residual tensile stresses in the glass matrix could overlap with external forces, predisposing crack propagation.

Compared with HC materials, LDGC presents higher flexural modulus, hardness, fracture toughness, and modulus of elasticity, with flexural strength comparable to that of HCs (Goujat et al., 2018; Furtado De Mendonca et al., 2019). LDGC crowns, inlays, and onlays are viable for posterior use. However, LDGC in three-unit inlay-retained fixed dental prostheses have presented a high failure rate (73%) in the premolar and molar regions, with fractures and debondings as the main failure modes (Becker et al., 2019).

2.4 Stress Distribution in Restored Tooth

2.4.1 Preparation Design

When restorative treatment is considered, the width of the isthmus, preservation of the marginal ridge, oblique and transversal crests, cavity depth and width, and rounded internal angles are important characteristics (Peumans et al., 2020). For MOD-cavities, in addition to the composite layering technique, cavity wall deflection has been found to decrease with increasing thickness of the wall (Kim et al., 2016). The highest principal stress could be observed in the internal angle of an MOD-cavity due to polymerization shrinkage and deflection of the cavity wall. Also, tooth preparation design may influence stress distribution in a restored tooth, as increasing the MOD cavity margin angle exposes teeth to fractures (Ausiello et al., 2017).

For ceramic onlays, preparation design might have a greater influence on stress concentration than the type of ceramic, possibly due to sharp angles in box preparations (Vianna et al., 2018). Therefore, sharp angles should be rounded, and a homogeneous thickness of ceramic may be favorable for stress distribution (Vianna et al., 2018). However, there is no clear consensus regarding favorable preparation designs. For example, *in vitro* studies have found that cuspal coverage preparation for indirect glass ceramic is not advantageous from the perspective of fracture resistance (Guess et al., 2013a; Soares et al., 2006). Conversely, Opdam et al. (2008) reported that direct resin composite cuspal coverage increased the survival rate of painful cracked teeth compared with teeth restored without cuspal coverage, perhaps due to decreased stress not only within the adhesive layer but also within the uncovered cusp. Differences in the above-mentioned studies may be attributed to different restorative materials, preparation designs, and testing setups.

Although a minimally invasive preparation technique should be adopted, mechanical retention is needed for indirect restoration to resist masticatory forces. Minimal axial wall height preparation could be considered for indirect occlusal restorations, as 1–2 mm axial wall height can ensure satisfactory retention for adhesively luted crowns (Gillette et al., 2016; Wake et al., 2019). However, the effect of certain preparation designs in clinical situations might be questionable, as preparation characteristics such as the number of surfaces and cusps involved, relative preparation width, and relative surface area of the restoration did not affect the success rate of LDGC restorations in a clinical study with a mean evaluation period of 37 months (Hofsteenge et al., 2024).

2.4.2 Material Properties

It is essential to consider the influence of material properties on stress distribution in a restored tooth. According to FEA analysis, increasing the elastic modulus of the restorative material increases stresses in the restoration and dentin while reducing stress at the cement layer, and thus, residual tooth structure may be exposed to cracks (Zhu et al., 2017). It has also been suggested that resin composites with a lower elastic modulus compared with ceramics may lead to favorable stress distribution in indirect restorations relying on retention from the pulp chamber of endodontically treated teeth (*i.e.* endocrowns) through deformation, potentially reducing the risk of tooth fracture (Zhu et al., 2017). This contrasts with another study reporting that with low elastic modulus materials, an increased amount of stress might be concentrated within the tooth preparation, promoting tooth fracture (Özkir, 2018). Avoiding stress concentration within the restorative material might be advantageous for occlusal veneers, which is achieved by using low elastic modulus materials (Tribst et al., 2018). Nevertheless, existing literature describes that stiff and non-stress-absorbing materials with a high elastic modulus may be favorable when treating cracked teeth (Kim et al., 2021; Liu et al., 2025). This is possibly due to the prevention of horizontal separation of crack walls, which may occur with high elastic modulus materials (Kim et al., 2021; Liu et al., 2025). Further mechanical studies are needed to better understand the influence of restorative material selection on stress distribution and behavior under loading. It is also noteworthy that as aging decreases bond strength between the indirect restoration and the tooth surface, stress distribution within a restored tooth under loading might be altered.

2.4.3 Thickness of Restoration

In addition to preparation design and material selection, evidence suggests that the thickness of the restoration may influence stress distribution. When the thickness of a resin composite restoration was analyzed, increasing thickness was found to be beneficial for even stress distribution of a restored tooth, in which tensile stress distribution was more uniform compared with models with thinner restorations (Panahandeh et al., 2017). Restoration thickness might also determine restorative material selection. Velho et al. (2023) reported that resin composites might be favorable for small thicknesses because of higher fatigue resistance compared with thin LDGC occlusal veneers. However, when the thickness is increased, artificial teeth restored with LDGC occlusal veneers provided higher fatigue resistance (Velho et al., 2023). Despite heterogeneity in data regarding the minimal thickness of occlusal veneers, promising mechanical performance of thin (0.3–0.8 mm) non-retentive LDGC and resin composite occlusal veneers has been reported in a systematic review including mostly *in vitro* studies (Alghauli et al., 2023). Minimal restoration thickness and, hence, conservative cavity preparation may be advantageous for resin-based CAD/CAM restorations but not for CAD/CAM ceramics (Zimmermann et al., 2019). This might be due to the mechanical properties of materials, as thin LDGC restoration concentrates stress within the restoration (Tribst et al., 2019), whereas thin HC occlusal veneers transfer stress from occlusal veneer to tooth preparation. These findings are supported by FEA analyses (Zhu et al., 2017; Tribst et al., 2018) although thin (0.6 mm) LDGC occlusal veneers can also withstand masticatory loads.

Existing literature draws attention towards minimal restoration thickness in the posterior region. Adequate performance of ultrathin resin composite and LDGC has been reported in a laboratory study with thicknesses of 0.3–0.5 mm (Heck et al., 2019) and in a clinical trial for teeth restored with LDGC or resin composite occlusal veneers with a thickness of 0.55–1.00 mm (Schlichting et al., 2022). A study by Sasse et al. (2015) suggested that using 0.7–1.0 mm thick LDGC occlusal veneers could be satisfactory for posterior teeth (Sasse et al., 2015). According to another study, sufficient load-bearing capacities were observed for LDGC and HC occlusal veneers with thicknesses of 0.5

mm and 1.0 mm (Ioannidis et al., 2019). The advantage of thin LDGC restorations is the preservation of dental tissue, which could result in a less destructive failure mode (Guess et al., 2013a).

2.4.4 Cement Layer

In the structure of a restored tooth, the resin composite cement layer thickness is also involved in stress distribution. However, the effect of cement layer thickness on stress distribution is not well established. There are reports stating that with increasing cement layer thickness, fracture load is reduced under both static loading (Tuntiprawon and Wilson, 1995; May et al., 2012; Rojpaibool and Leevailoj, 2017) and cyclic loading conditions (Bottino et al., 2015; May et al., 2015). This finding has been explained by increased polymerization shrinkage stress in a thicker cement layer, resulting in the generation of tensile stress within ceramic crowns (May et al., 2012). However, hygroscopic expansion caused by water sorption could partly relieve tensile stresses at the adhesive interface of ceramic crowns, reducing shrinkage in a thick cement layer (May et al., 2015).

Variations (± 50 µm) in internal adaptation of ceramic crowns are common with both heat-pressed and CAD/CAM produced milled crowns (Akın et al., 2015). It has been shown that increasing cement layer thickness above 300 µm decreased fracture load of glass ceramic plates under simulated loading test conditions (Scherrer et al., 1994). Conversely, Prakki et al. (2007) reported that for 1 mm thick ceramic plates, increasing cement layer thickness increased fracture load. For 2 mm thick plates, cement layer thickness had no influence on fracture load (Prakki et al., 2007).

In a study by Tribst et al. (2018), FEA analysis showed that variation in cement layer thickness (100, 200, and 300 µm) did not affect stress distribution or mechanical performance of a restored tooth. In fact, decreasing the thickness and elastic modulus of the restorative material increased tensile stress at the cement layer, exposing restoration to debondings (Tribst et al., 2018). The low elastic modulus of resin cement compared with ceramics may lead to tensile stress at the ceramic bonding surface during loading, which is emphasized by a thick cement layer and water-aging (Silva et al., 2008).

2.5 Bonding of Direct and Indirect Restorative Materials

2.5.1 Bonding of Direct Restorations

Good bonding between the restoration and dental tissues is essential for achieving a long-lasting restoration. In adhesive restorations, bonding is based on dentin and enamel pretreatment with acid etching, primers, and adhesives. For indirect restorations, the adhesion of the cement to the restorative materials plays a significant role too. Figure 1 schematically illustrates the structure of the adhesive joint between the tooth and the indirect restorative material.

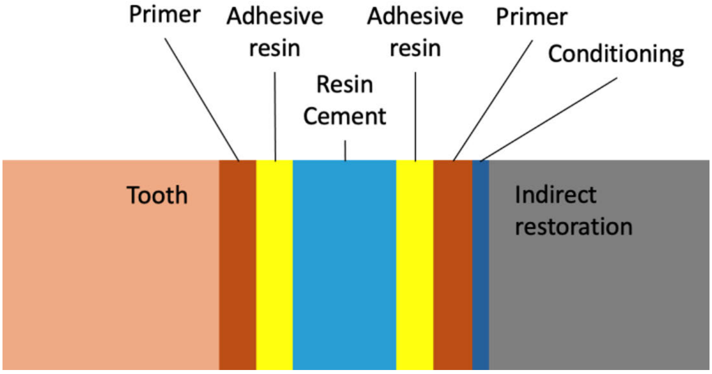


Figure 1. Schematic representation of adhesive joint between tooth substance and indirect restorative material.

2.5.1.1 Bonding to Dentin and Enamel

Dental adhesives are used to form a hybrid layer, where resin composite is infiltrated between the collagen fibers of dentin (Van Meerbeek et al., 2003). In the etch-and-rinse approach, inorganic hydroxyapatite is removed from the surface of dental tissue by phosphoric acid, creating microporosities on enamel and exposing collagen in dentin (Van Meerbeek et al., 2003). During priming, water in the exposed collagen network is replaced by the adhesive, followed by a bonding agent creating a 4–5 µm-thick hybrid layer (Breschi et al., 2018; Van Meerbeek et al., 2003). Although etch-and-rinse adhesives may provide the highest bond strength for direct restorations to enamel and dentin (Masarwa et al., 2016), the self-etch approach has been presented as a less time-consuming and less technique sensitive approach (Alghauli et al., 2023). In the self-etch approach, instead of a separate acid-etching step, acidic monomers are included in the adhesive to demineralize hydroxyapatite, although separate enamel etching is recommended (Rosa et al., 2015; Alghauli et al., 2023). Acidic monomers also enable formation of chemical bonds between resin monomers and hydroxyapatite in dentin (David et al., 2022). However, the bond strength of self-adhesive resin composite was found to be inferior compared with conventional resin composites using an adhesive system (David et al., 2022).

2.5.2 Bonding of Indirect Restorations

For successful restoration, a high bond strength of the luting cement to both the restorative material and dental tissues is essential. One of the shortcomings of indirect resin composite material is debonding, which is a major reason for failure in indirect resin composites (Kabetani et al., 2022). Variables such as the type of tooth, vertical dimension and taper of the tooth preparation, luting cement, and the occlusal thickness of the restoration influence crown debonding events (Kabetani et al., 2022). Bonding to indirect resin composite is complicated, as dissolution of adhesive resin into the cross-linked resin matrix is not allowed, and bonding relies mainly on micromechanical retention (Vallittu, 2009). Hence, optimal bonding requires pretreatment (conditioning) to coarse the bonding surface of resin composite. For this procedure, sandblasting and hydrofluoric acid etching might be optimal for indirect resin composites (Lise et al., 2017; Muhammed et al., 2023; Beltrami et al., 2024), although sandblasting may result in a rougher surface than hydrofluoric acid in resin composites (Özcan and Vallittu, 2003; Özcan et al., 2005). There are also results showing that hydrofluoric acid is not enhancing bonding between indirect resin composites and HCs (Özcan et al., 2005).

Micromechanical retention may also depend on the filler loading in indirect resin composite, as exposed filler particles enable chemical bonding to resin monomers via silane (Mangoush et al., 2021). Both pretreatment methods and luting cements may influence the bond strength of indirect materials (Peumans et al., 2016). Therefore, appropriate resin cement must be selected based on the restorative material. Although conventional adhesive resin cements might ensure higher bond strength, self-adhesive resin cements simplify the bonding procedure and may present acceptable bond strength when coupled with their recommended adhesive (Maravić et al., 2023). In addition to cement type, filler content in resin cement may influence the bond strength of HC restorations (Cekic-Nagas et al., 2016). Before bonding cement application, silanization of the surface of the restorative material serves two important functions: firstly, it improves surface wettability, allowing penetration of resin monomers into micropores of the etched surface, and secondly, it enables chemical bonding between glass ceramic and resin monomers (Matinlinna et al. 2004; Ramakrishnaiah et al., 2018). However, the silane-promoted adhesive interface might be prone to hydrolysis in the presence of water (Heikkinen et al., 2009; Heikkinen et al., 2013; Ramakrisnaiah et al., 2018).

Water-aging has been shown to decrease the strength of adhesion between resin cement and CAD/CAM materials (Ustun and Ayaz, 2021). However, when it comes to the adhesive interface between resin cement and glass ceramic, both micromechanical and chemical interactions are fundamental for sufficient adhesive strength. Results by Frankenberger et al. (2015) and Peumans et al. (2016) indicate that in addition to chemical adhesion, micromechanical adhesion is also needed for LDGC, as only silanization resulted in lower bond strength compared with hydrofluoric acid etching and silanization. For pretreatment of LDGC, hydrofluoric acid etching followed by silanization has resulted in higher micro-tensile bond strength (µTBS) compared with sandblasting (Frankenberger et al., 2015) or tribochemical silica coating (conditioning) (Peumans et al., 2016). Both of these studies also found higher µTBS for LDGC compared with HCs (Frankenberger et al., 2015; Peumans et al., 2016). However, surface conditioning for increasing the surface roughness is not without problems either: a roughened surface contains microscopic precracks which might impair the flexural strength of glass ceramics (May et al., 2022). On the other hand, properly made cementation after silane priming allows microcracks to be filled with resin and seals the surface, which with the appropriate cement-ceramic combination, increases the strength of the glass ceramic (da Rosa et al., 2022). When studying the strengthening effect of resin cement in more detail, Fleming et al. (2012) found that increasing the flexural modulus of resin cement and the cement layer thickness, biaxial flexure stress of resin-bonded glass ceramic plates are increased. Nevertheless, it is unclear whether the choice of resin cement for LDGC restorations influences the clinical performance of restored teeth especially as in a one-year follow-up study, conventional resin cement and self-adhesive resin cement presented comparable clinical performance (Sousa et al., 2020).

Current evidence indicates that both direct and indirect restorative materials can successfully rehabilitate posterior teeth. Their clinical performance depends on several factors, including material selection, preparation design, bonding protocol, and restoration thickness. However, the literature also reports contradictory findings, and the specific influence of many of these factors on the mechanical performance of restored teeth remains uncertain.

3 Aims

This doctoral study examined variables affecting the fracture load of occlusally restored tooth using indirect and direct restorations. Several factors, such as the type of restorative material, bonding to the underlying tooth, shape of the preparation, and thickness of the occlusal veneer and cement layer were considered important for the tooth to withstand high occlusal loads. According to the working hypothesis, these factors are critical for the durability of a restored tooth.

The aims of this doctoral study were:

1. To evaluate the influence of a rounded MOD-cavity design and inlay bonding on the load-bearing capacity of a tooth restored with HC inlay restorations (Study I).

2. To evaluate the influence of chamfer preparation, the type of restorative material (HC and LDGC) and occlusal veneer bonding on the load-bearing capacity of a restored tooth (Study II).

3. To evaluate the influence of the type of material and thickness of the occlusal veneer and cement layer on the load-bearing capacity of a tooth restored with HC and LDGC occlusal veneers (Study III).

4. To study the influence of direct flowable and condensable PFC and flowable SFRC occlusal veneers on the fracture load of the restored tooth after 1 day and 6 months of water storage (Study IV).

4 Materials and Methods

Materials used to prepare the specimens in each Study (I–IV) are listed in Table 1.

Table 1. Materials used in studies I–IV.

Material	Composition	LOT	Manufacturer	Study
Scotchbond Universal Etchant	37% Phosphoric acid	9250920, 6115193	Solventum, Neuss, Germany	I, II, III
Blue Etch	36% o-phosphoric acid	0602231	PPH Cerkamed, Stalowa Wola, Poland	IV
IPS Ceramic Etching Gel	4.5% Hydrofluoric acid	Y03912, Z037BV	Ivoclar Vivadent, Schaan, Liechtenstein	I, II, III
G-Multi Primer	Ethyl alcohol (90–100%), MDP, MDTP, silane	2010191, 2102051, 2202071	GC Europe, Leuven, Belgium	I, II, III
Adhesive Enhancing Primer	Ethyl alcohol (25–50%), MDP, 4-MET, MDTP	2012021, 2206271	GC Corporation, Tokyo, Japan	I, II, III
G2 Bond Universal Primer	4-MET, 10-MDP, DMA, BHT, photoinitiator, acetone, water	2305181	GC Corporation, Tokyo, Japan	IV
G2 Bond Universal Adhesive	UDMA, DMA, photoinitiator, silica, BHT	2304191	GC Corporation, Tokyo, Japan	IV
G-CEM ONE Self-Adhesive Resin Cement	UDMA, DMA, MDP, inhibitor, initiator, fluoro-alumino-silicate glass, silicon dioxide	2201121, 2304121, 2010291, 2010261, 2010281	GC Europe, Leuven, Belgium	I, II, III
Cerasmart 270	71wt% silica (20nm) and barium glass (300nm) nanoparticles, Bis-MEPP, UDMA, DMA	1906036, 1903281, 2104141, 2101281, 2011161, 2102101, 2102021, 2103011	GC Corporation, Tokyo, Japan	I, II, III
IPS e.max CAD	SiO_2 57–80wt%, Li_2O 11–19wt%, K_2O 0–13wt%, P_2O_5 0–11wt% and other oxides.	W02812, W34762, V37852, V44582,	Ivoclar Vivadent, Schaan, Liechtenstein	II, III

		Z033G5, YB54P7		
everX Flow, dentin shade	Bis-MEPP, TEGDMA, UDMA, micrometer scale glass fiber (fiber length 140µm, diameter 6µm, 25wt%) and barium glass (42–52wt%)	2212261, 2202021, 2310261	GC Corporation, Tokyo, Japan	IV
G-ænial Universal Injectable	Dimethacrylate monomers 31wt%, Barium glass 150nm and silica (fillers 69wt%)	2203141, 2310271, 2311061	GC Corporation, Tokyo, Japan	IV
Essentia Universal	UDMA, BisEMA, BisGMA, TEGDMA, Bis-MEPP, Prepolymerized silica (16–17 µm) and barium glass (>100nm, fillers 81wt%)	2303291, 2312051	GC Corporation, Tokyo, Japan	IV

MDP = 10-Methacryloyloxydecyl dihydrogen phosphate, MDTP = 10-methacryloyloxydecyl dihydrogen thiophosphate, 4-MET = 4-[2-(methacryloyloxy)ethoxycarbonyl]phthalic acid, Bis-MEPP = bisphenol-A- ethoxylate dimethacrylate, UDMA = urethane dimethacrylate, DMA= dimethacrylate, TEGDMA = Triethylene glycol dimethacrylate, BisEMA: ethoxylated bisphenol-A-dimethacrylate, BisGMA = bisphenol-A-glycidyl methacrylate, BHT = butylated hydroxytoluene.

4.1 Preparation of Tooth

Extracted human molar teeth of approximately the same size were selected for the study. An acceptable variation in the dimensions of the teeth was 1 mm, and the teeth were stored in 0.1% thymol solution until use. Teeth were prepared using diamond rotary instruments under water cooling. Sample sizes in the groups were determined based on previous literature.

In Study I, 48 molars (n = 12/group) were selected and randomly allocated to four groups. The teeth were prepared for standardized MOD cavities with both the width and the depth of the cavities set at 4 mm. Internal angles were prepared either as edge-shaped or rounded designs, as demonstrated in Figure 2.

In Studies II, III, and IV, 64 (n = 8/group), 64 (n = 8/group) and 60 (n = 10/group) molar teeth, respectively, were selected and randomly assigned to groups. In each of these studies, a flat occlusal surface was prepared with dentin in the center, surrounded by enamel margins, simulating a worn tooth. In Study II, a flat occlusal surface was prepared either with or without a chamfer preparation, and in Study III, a flat occlusal surface was prepared with a chamfer for occlusal veneers (Figure 3). Prior to tooth preparation in Study IV, teeth were attached to autopolymerizing poly(methyl methacrylate) (PMMA) blocks made by combining polymer powder and monomer liquid (Self

Curing, Vertex-Dental B.V., Soesterberg, the Netherlands) at a powder/liquid ratio of 1.7 g/1 ml. Then, conventional silicone impressions were individually acquired for each tooth by mixing putty base and activator (Silikon-Knetmasse, Orbis, Münster, Germany) and sectioned from the central fossa to control the preparation depth of 2 mm from the central fossa (Figure 4). Also, translucent vinyl polysiloxane impressions (Exaclear, GC Corporation, Tokyo, Japan) were individually obtained for each tooth to serve as molds for the restorative procedure (Figure 5).

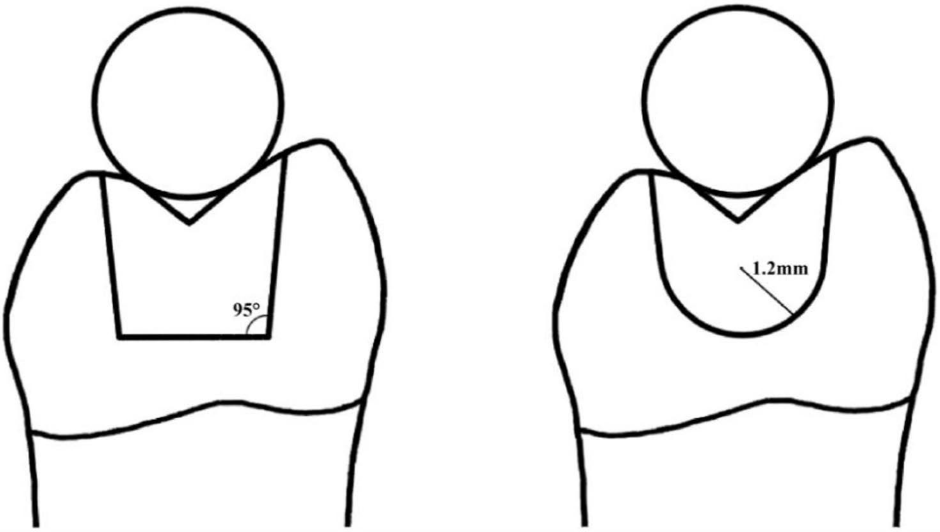


Figure 2. Schematic representation of both edge-shaped and rounded MOD-cavity bottom designs and restoration, and metal ball in contact with the inlay restoration in loading test. Adapted from original publication I.

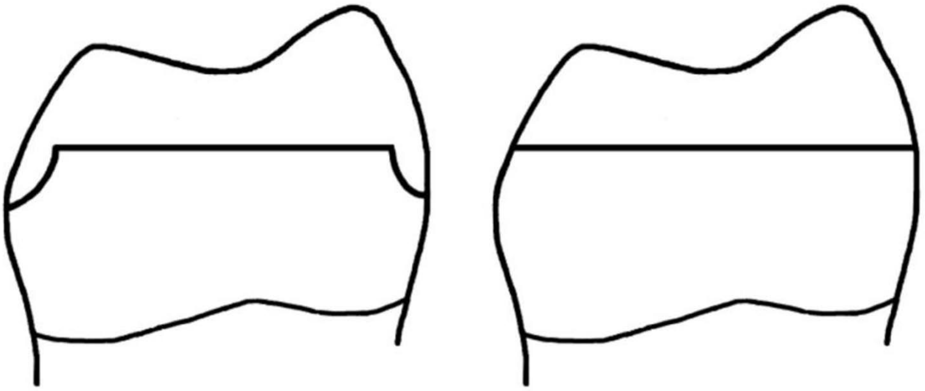


Figure 3. Schematic representation of restored teeth with both flat and chamfer preparations.

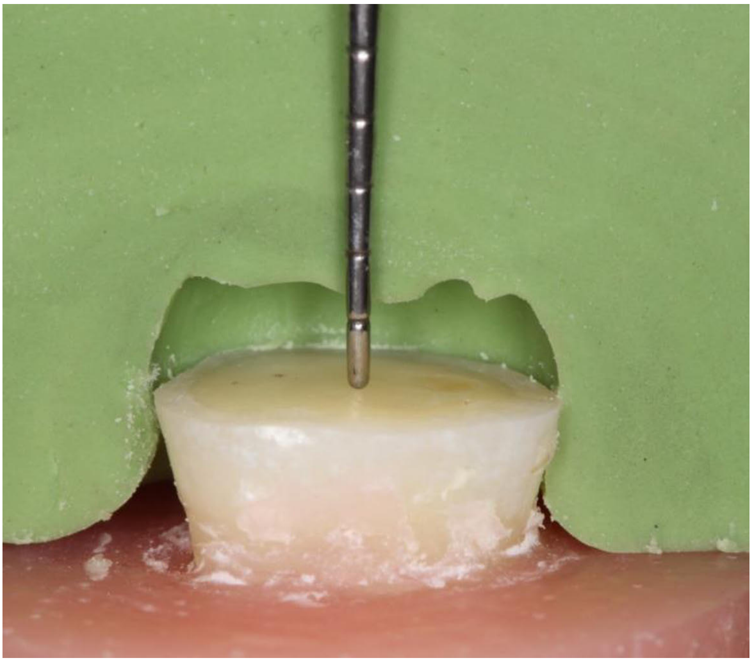


Figure 4. Preparation showing cavity dimensions (3 mm) from the bottom of the prepared flat surface to the occlusal surface. The first mark on the periodontal probe is on 2 mm from the tip. Adapted from original publication IV.

Figure 5. An example of the translucent silicone key used to fabricate the occlusal veneers. Adapted from original publication IV.

4.1 Manufacturing of Restorations

4.1.1 CAD/CAM-technique (I, II, III)

In Studies I, II, and III, tooth preparations were scanned, and indirect restorations were designed and milled using CAD/CAM technology (Omnicam, CEREC AC SW5.1.3, and CEREC MC XL, Dentsply Sirona, Bensheim, Germany). In Study I, inlays were milled from HC (Cerasmart270, GC Corporation, Tokyo, Japan) whereas in Studies II and III, occlusal veneers were milled from either HC (Cerasmart270, GC Corporation, Tokyo, Japan) or LDGC (IPS e.max CAD, Ivoclar Vivadent, Schaan, Liechtenstein). In Studies I–III, restorations were designed with as similar occlusal morphology as possible using a selected model tooth according to which the occlusal anatomy of the restorations was designed for each tooth preparation. Thickness of the occlusal veneers and the cement layer was determined using CAD/CAM software. In Study II, the thickness of the occlusal veneer was 3.0 mm at the cusps and 1.9 mm at the central fossa. In Study III, occlusal veneer thickness was set at either 0.5 mm or 1.8 mm at the central fossa and either 1.7 mm or 3.0 mm at the cusps. Also, in Study III, thickness of either 50 µm or 200 µm were selected for the cement layer. After milling, LDGC occlusal veneers were polished using diamond polisher cups (OptraFine, Ivoclar Vivadent, Schaan, Liechtenstein), glazed (IPS Glazing Paste, Ivoclar Vivadent, Schaan, Liechtenstein), and crystallized in a furnace (Programat P300/G2, Ivoclar Vivadent, Schaan, Liechtenstein). By using auxiliary firing paste (IPS Object fix, Ivoclar Vivadent, Schaan, Liechtenstein), direct contact between LDGC occlusal veneers and the crystallization tray in the furnace was avoided. Following crystallization, LDGC occlusal veneers were cleaned with an ultrasonic bath for 15 minutes in Study II and with a steamer (Wasi-Steam, Wassermann Dental-Maschinen Gmbh, Hamburg, Germany) in Study III. All HC restorations were polished using silicone polishers and polishing spirals (Sof-Lex, Solventum, Neuss, Germany).

4.1.2 Bonding Procedure (I, II, III, IV)

For pretreatment, HC inlays and occlusal veneers were etched for 60 seconds and LDGC occlusal veneers were etched for 20 seconds using 4.5% hydrofluoric acid (IPS Ceramic Etching Gel, Ivoclar Vivadent, Schaan, Liechtenstein). G-Multi Primer (GC Corporation, Tokyo, Japan) was applied to the etched surface of indirect restorations with a microbrush and gently air-dried. The enamel of the prepared teeth was selectively etched with 37%

phosphoric acid (Scotchbond Universal Etchant, Solventum, Neuss, Germany) for 15 seconds, rinsed with distilled type I water, and gently air-dried. After selective etching, the tooth preparation was treated with a primer (Adhesive Enhancing Primer, GC Corporation, Tokyo, Japan) using a microbrush for 10 seconds and air-dried with maximum pressure for 5 seconds as per manufacturer instructions. Self-adhesive resin cement (G-CEM ONE, GC Corporation, Tokyo, Japan) was slowly applied onto the bonding surface of the restoration with the tip of the syringe in contact with the indirect restoration, which was thereafter pressed onto the preparation using moderate pressure. In studies I and II, excess cement was removed, and the cement was photopolymerized for 10 seconds on each side of the restoration (1400 mW/cm^2, D-Light Pro, GC Corporation, Tokyo, Japan) by keeping the light tip in contact with the restoration. In Study III, restored teeth were light cured for 20 seconds occlusally and 10 seconds from each side of the veneer with similar light-curing settings as in studies I and II.

In studies I and II, non-bonded specimens were manufactured by applying n-hexane wax on the internal surface of the indirect restoration to interrupt the formation of the adhesive interface. These specimens underwent the same selective enamel etching, primer, and self-adhesive resin cement application as the bonded specimens. After restoration bonding in Studies I–III, restored teeth were stored in distilled type I water for 1 day at room temperature before the loading test.

For direct restorations in Study IV, the enamel of the tooth preparation was etched with 36% o-phosphoric acid (Blue Etch, Cerkamed, Stalowa Wola, Poland) for 15 seconds, water-rinsed thoroughly, and carefully air-dried. The primer (G2 Bond Universal, GC Corporation, Tokyo, Japan) was applied thoroughly to the prepared tooth surface, brushed for 10 seconds with a microbrush, and air-dried for 5 seconds. After the primer, the adhesive (G2 Bond Universal, GC Corporation, Tokyo, Japan) was applied to the preparation surface, gently air dried, and light-cured (Elipar LED, TM S10, Solventum, Seefeld, Germany) for 20 seconds with a light intensity of 1200 mW/cm^2 according to the manufacturer instructions.

4.1.3 Application of Direct Restorations (IV)

In Study IV, flowable and condensable PFC (G-ænial Universal Injectable and Essentia Universal, GC Corporation, Tokyo, Japan) and a flowable SFRC (everX Flow, dentin shade, GC Corporation, Tokyo, Japan) were selected as restorative materials. For flowable PFC, two perforations were made in the translucent polysiloxane injection mold with a metal syringe tip, one for injection of the flowable composite and the other for removing of excess material and air. For SFRC, slightly wider perforations were prepared with a diamond rotary instrument through the injection mold to avoid distortion of the plastic syringe tip. During injection of the flowable composites onto the preparation, the tip of the syringe was placed in contact with the prepared tooth surface and slightly withdrawn from the preparation surface. For restoring teeth with condensable PFC, the condensable PFC material was placed into the mold, which was pressed onto the preparation. Two perforations were also prepared through the translucent mold to remove excess condensable PFC material. Each direct occlusal veneer was light cured for 20 seconds from each side through the injection mold with a light intensity of 1200 mW/cm^2 (Elipar LED, TM S10, Solventum, Seefeld, Germany) for 40 seconds from each side from a distance of approximately 1 mm after removing the injection mold. The restorations were polished, and prior to the quasi-static loading test, half of the restored teeth were stored for 1 day and the other half for 6 months in distilled type I water at 37 degrees Celcius.

4.2 Mechanical Tests

4.2.1 Loading Test (I, II, III, IV)

For the loading test of restored teeth, cylindrical PMMA blocks (Vertex-Dental B.V.) were manufactured. Cavities were drilled into the PMMA blocks to attach restored teeth with additional PMMA (Vertex-Dental B.V.). An LR30K Plus loading machine was used for the quasi-static loading test in air at room temperature with either a 2.5 kilonewton (kN) loadcell (Study I, Lloyd Instruments/Ametek Inc., Fareham, UK) or a 30 kN loadcell (studies II–IV, Lloyd Instruments/Ametek Inc., Fareham, UK). During the quasi-static loading tests, each restored tooth was loaded through a steel ball (5.5 mm diameter) vertically along the long axis of the restored tooth at a crosshead speed of 1 mm per minute until fracture. Fracture load in newtons (N) was recorded. Also, load-deformation curves were acquired from the loading processes.

4.2.2 Surface Microindentation Test for Surface Hardness (III)

In Study III, cement disks of 1 mm thickness (n = 20) were manufactured from the self-adhesive resin cement (G-CEM ONE, GC Corporation, Tokyo, Japan). To test the surface hardness of dried and wet cement disks, they were either stored in a desiccator (n = 10) or in distilled type I water (n = 10) at 37 degrees Celcius for 12 days until the weights of the disks were stabilized. All disks were then attached to a metal plate functioning as a template for the surface indentation test and loaded with a diamond tip for 30 seconds using a 10 N load, with both loading and unloading times being 30 seconds. Each cement disk was loaded four times at separate locations of the surface (SMT-5000, Rtec instruments, Oakland, San Jose, USA).

4.3 Analyses

4.3.1 Visual Examination of Fractured Tooth (I, II, III, IV)

After the loading test, fracture types were analyzed and classified visually according to the type of fracture of restored teeth.

In Study I, fracture types were classified as fracture of two cusps, fracture of one cusp and fractured veneer. Cuspal fractures also included partial fracture of the occlusal veneer. In Study II, fracture types were classified either as partial tooth fracture, complete tooth fracture, in which the whole crown was fractured, or loosened restoration. In a loosened restoration, the occlusal veneer fractured and the underlying tooth remained without visible fractures.

In Study III, fractures were classified as fractured tooth or fractured veneer. In a fractured tooth, fractures of both the occlusal veneer and the tooth preparation were detected. In a fractured veneer, fracture of the occlusal veneer was detected without visible fractures of the adjacent tooth preparation. In Study IV, fracture types were classified based on the depth of fracture. Fractures were classified as either repairable or non-repairable fractures. Repairable fractures presented a cohesive fracture of the restorative material with an intact tooth, superficial tooth fracture (delamination of enamel) above the cementoenamel junction (CEJ) or a cohesive tooth fracture above or at the CEJ. In non-repairable fractures, a fracture of the restored tooth below CEJ was present.

4.3.2 Load-deformation Curves (I, II, III, IV)

During quasi-static loading, load-deformation curves were recorded from each test specimen. One curve per group was presented based on the mean fracture load, mean deformation, and the most typical behavior of the restored tooth during loading.

4.3.3 Microscopic Analysis (II, III)

In Study II, scanning electron microscopy (SEM) examination was performed with a magnification of 250x (JSM 5500, JEOL Ltd., Tokyo, Japan) to determine possible resin cement remnants on the bonding surface of the occlusal veneer in both bonded and non-bonded groups after the loading test. After the loading test, fractured pieces of occlusal veneers were stored in a desiccator for 1 week for imaging. Fractured veneers were coated with a gold layer by using a sputter coater in a vacuum evaporator (BAL-TEC SCD 050 Sputter Coater, Balzers, Liechtenstein).

In Study III, to determine fracture type from the cross-sectional pieces of the fractured veneer and tooth structure, one fractured piece from each group was visually analyzed under SEM (JSM 5500, JEOL Ltd., Tokyo, Japan) with a magnification of 25x after coating with a gold layer in a vacuum evaporator (BAL-TEC SCD 050 Sputter Coater, Balzers, Liechtenstein).

4.3.4 Micro-computed Tomography Imaging (IV)

Restored teeth stored in water for 6 months (n = 10/material) in Study IV were imaged using high-resolution desktop micro-computed tomography (µCT, Bruker Skyscan 1272, Kontich, Belgium) to identify possible internal voids within each occlusal veneer. To stabilize the restored teeth during the scanning process, each tooth was attached to a PMMA block mounted on a sample rod using transparent orthodontic dental wax and parafilm sealing film, ensuring rotational stability and limiting water evaporation during scanning. The following scanning parameters for restored teeth were used: 80 kilovolts source voltage, 125 microamperes source current, 1 mm aluminum filter, 9.0 µm pixel size, and 0.200-degree rotation step. To construct cross-sectional images of the scanned teeth, NRecon 1.7.5.6 software (Bruker Skyscan 1272, Kontich, Belgium) was used with parameters: 0.005–0.100 attenuation coefficient range, 4 smoothing, 6 ring artifact reduction, 60% beam hardening reduction. With the use of CTAn 1.23.0.2 software (Bruker Skyscan 1272, Kontich, Belgium), void volumes within each material were determined. The voids were selected by selecting threshold values of 0–10 of the 8-bit grayscale images. With image rendering program (CTVox 3.3.1, Bruker Skyscan 1272, Kontich, Belgium), visualization of scanned teeth and voids within the material was obtained.

4.3.5 Statistical Analysis (I, II, III, IV)

In Study I, as the distribution of fracture load values didn't meet the criteria of normal distribution as tested by the Shapiro-Wilk test, mean fracture load values between groups were compared by non-parametric Kruskal-Wallis test followed by multiple comparisons by Steel-Dwass test.

In Studies II and III, after confirming normal distribution of the fracture load data (Shapiro-Wilk test) a parametric three-way analysis of variance (ANOVA) was conducted followed by multiple comparisons by Tukey HSD test.

In Study IV, normal distribution of the fracture load results of each group was confirmed (Shapiro-Wilk test) and two-way ANOVA was used to compare the fracture load results between groups. Tukey HSD test was performed for multiple comparisons. Additionally, Welch's test was conducted to determine the statistical difference of relation of internal voids-to-restorative material volumetric ratio between the materials used. Also, the correlation between the fracture load and the internal voids-to-restorative material volumetric ratio was studied with the Pearson correlation test.

The data were analyzed using JMP®, Version 17. SAS Institute Inc., Cary, NC, 1989–2023, except with the Pearson correlation in Study IV, which was conducted using the SPSS program (IBM SPSS Statistics 29). $P < .05$ was considered as a statistically significant difference between compared groups.

5 Results

5.1 Mechanical Tests

5.1.1 Quasi-static Loading Test (I, II, III, IV)

5.1.1.1 Design of the Preparation (I, II)

Comparison of the effect of edge-shaped MOD-cavity design with rounded cavity design on fracture load was performed in Study I. No statistically significant difference was found between the two cavity designs (Figure 6). When comparing teeth restored with occlusal veneers with or without a chamfer preparation in Study II, no statistically significant differences in fracture load values were found between any of the groups with the same material and bonding protocol (Figure 7).

5.1.1.2 Bonding of the Restoration (I, II)

Bonding of the restorations influenced the fracture load. In Study I, bonded inlays presented statistically significantly higher fracture load than non-bonded specimens with both edge shaped and rounded cavity designs ($p \leq .0022$, Figure 6). In Study II, bonded and non-bonded HC occlusal veneers exhibited equal fracture load with or without a chamfer preparation. However, bonded LDGC occlusal veneers showed statistically significantly higher fracture load compared with any of the non-bonded veneers or bonded HC veneers ($p \leq .0007$, Figure 7).

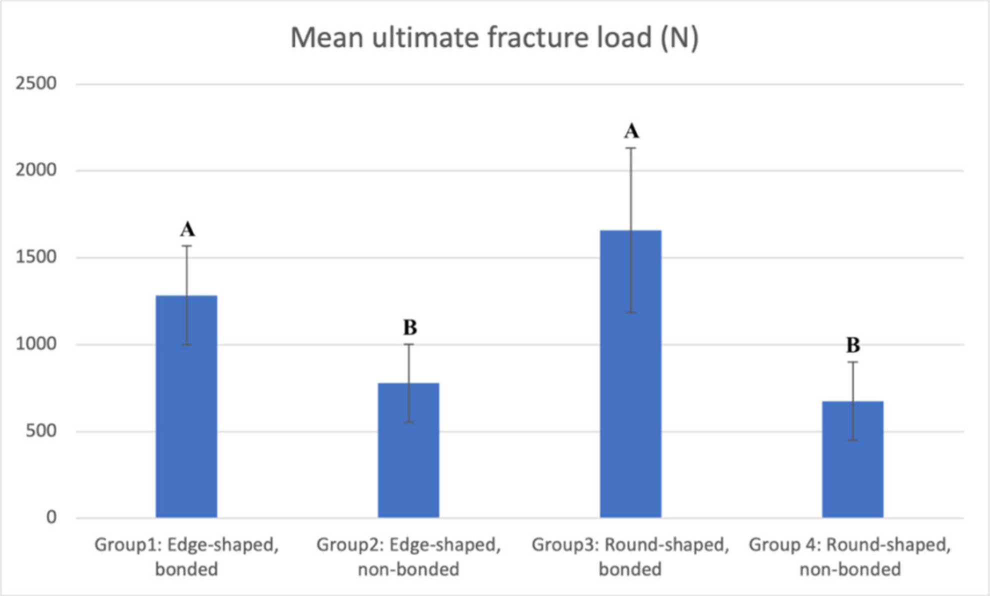


Figure 6. Mean ultimate fracture load (N) and standard deviation for each group in Study I. Groups not connected by the same letter on the column are statistically significantly different ($p < .05$). Adapted from original publication I.

5.1.1.3 Material Selection (II, III, IV)

In each study, material selection influenced the fracture load of the restored teeth. In Study II, teeth restored with LDGC occlusal veneers yielded superior fracture load compared with teeth restored with bonded or non-bonded HC occlusal veneers or non-bonded LDGC veneers ($p \leq .0007$, Figure 7). However, in Study III, teeth restored with 1.8 mm thick LDGC occlusal veneers presented similar fracture load compared with HC veneers (Figure 8).

In Study IV, teeth restored with direct SFRC occlusal veneers provided statistically significantly higher fracture load than those restored with flowable or condensable PFC occlusal veneers, regardless of water storage duration ($p < .0001$, Figure 9). Six months of water storage was not found to affect the fracture load of restored teeth ($p > .05$, Figure 9).

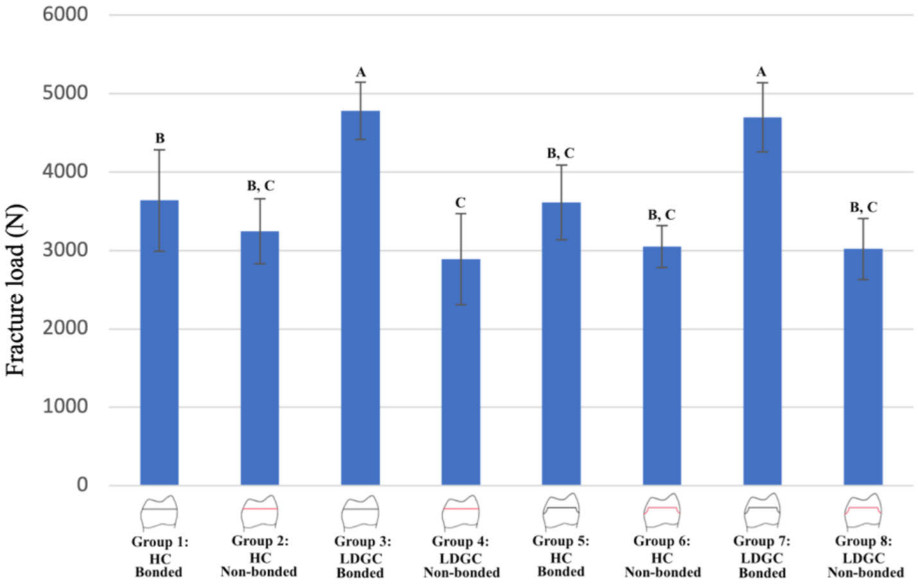


Figure 7. Mean ultimate fracture load within groups with standard deviations respectively for each group in Study II. Red line between tooth and restoration illustrates deteriorated bonding. Groups not connected by the same letter above the column are statistically significantly different (p < .05). HC = hybrid ceramic, LDGC = lithium-disilicate glass ceramic. Adapted from original publication II.

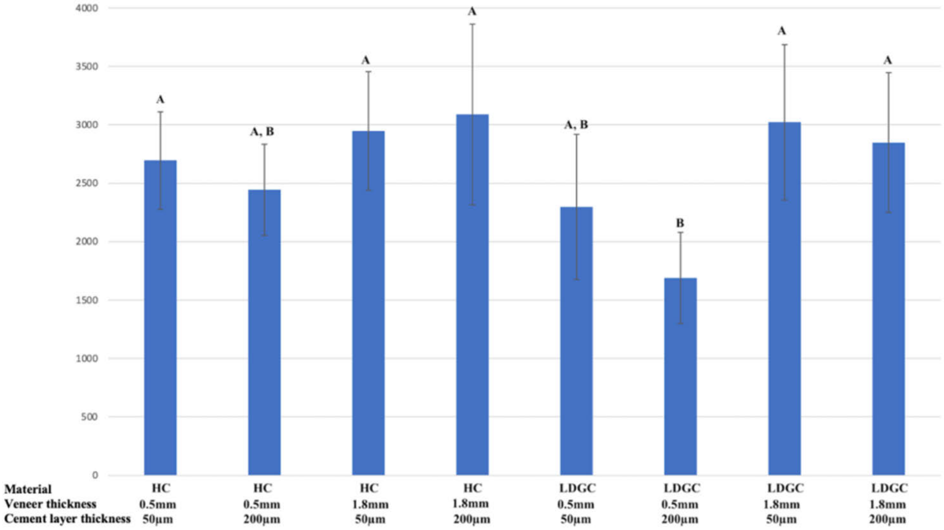


Figure 8. Mean fracture loads according to veneer material (HC and LDGC), thicknesses of veneer (0.5 mm or 1.8 mm) and cement layer (50 µm or 200 µm) in Study III. Groups not connected by the same letter are statistically significantly different (p < .05). HC = hybrid ceramic, LDGC = lithium-disilicate glass ceramic. Adapted from original publication III.

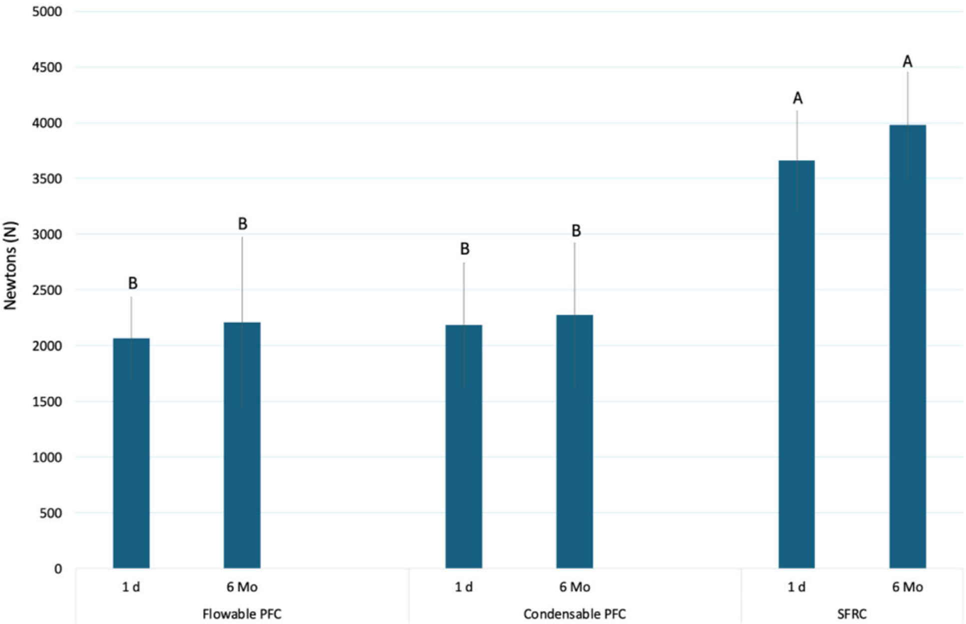


Figure 9. Fracture load values of tested restorations. Teeth were stored 1 day and 6 months in water at 37 degrees Celcius. Different letters above the columns indicate statistically significant difference ($p < .05$). PFC = particulate-filled composite, SFRC = short-fiber-reinforced composite. Adapted from original publication IV.

5.1.1.4 Thickness of Occlusal Veneer and Cement Layer (III)

Interestingly, it was found that variation in the thickness of the HC occlusal veneers did not influence the fracture load. As expected, 0.5 mm thick LDGC occlusal veneers recorded lower fracture load compared with 1.8 mm thick veneers, although the difference was not statistically significant between 1.8 mm thick veneers and 0.5 mm thick LDGC veneers with a cement layer thickness of 50 µm. Moreover, cement layer thickness had no influence on the fracture load of teeth restored with HC veneers (Figure 8). In teeth restored with LDGC veneers, increasing cement layer thickness tended to reduce fracture load, especially with 0.5 mm thick LDGC occlusal veneers with 200 µm cement layer, which had statistically significantly lower fracture load than teeth restored with 1.8 mm thick LDGC occlusal veneers ($p \leq .014$, Figure 8).

5.1.2 Surface Hardness (III)

After 12 days of water storage of cement disks in Study III, the mean water absorption of a cement disk was 1.2 percentage of weight (wt%). The surface microindentation test of dry and water-stored cement disks showed that dry cement disks recorded equivalent surface hardness to water-stored disks

(0.51 gigapascals [GPa] and 0.48 GPa, respectively) (Figure 10). Furthermore, there were no statistically significant difference in elastic recovery between dry and water-stored specimens (Figure 11).

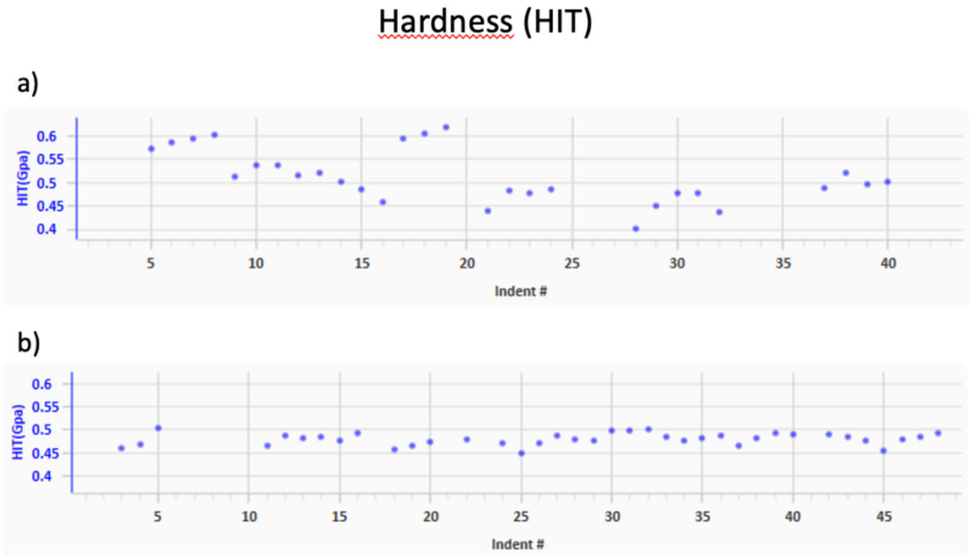


Figure 10. Mean surface microhardness indentation (HIT in GPa) of the a) dry and b) water-stored cement disks. Adapted from original publication III.

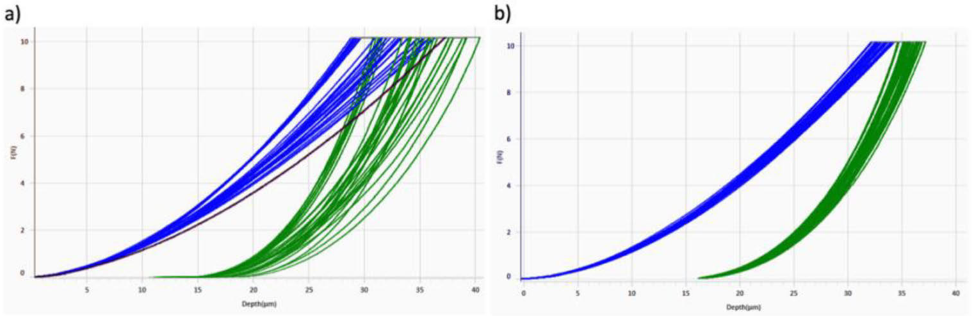


Figure 11. Applied load and indentation depth (µm) of a) dry and b) water-stored cement disks. Adapted from original publication III.

5.2 Deformation of Restored Tooth During Loading (I, II, III, IV)

In Study I, bonding was found to influence the behavior of restored teeth during loading. With bonded restorations, loads increased steadily without clear signs of precracks observed, whereas in non-bonded specimen fracture load was lower, and multiple precracks could be detected during the loading events (Figure 12).

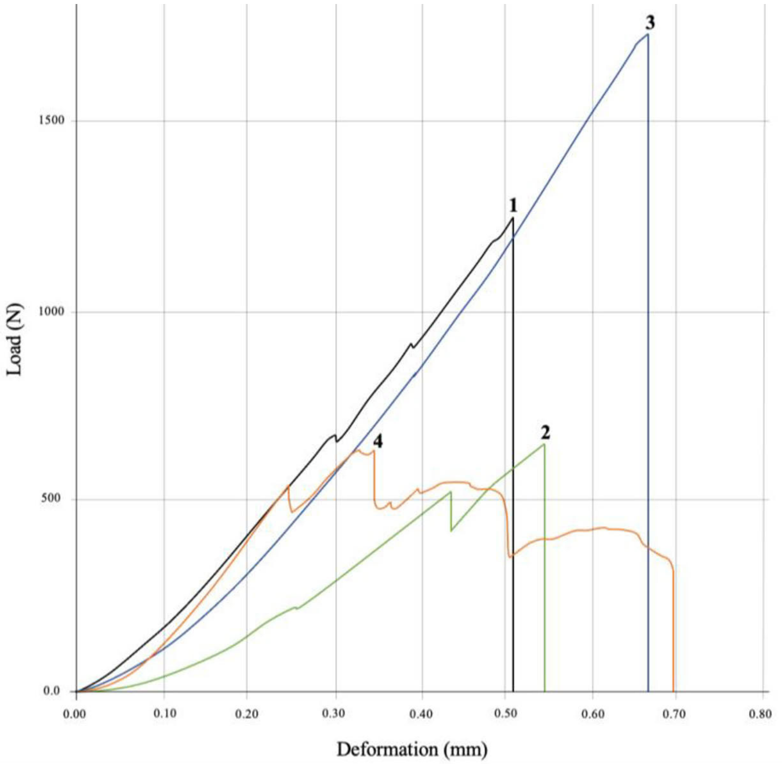


Figure 12. Load-deformation curves according to each group in Study I. Groups are described as 1 = edge-shaped cavity, bonded inlay; 2 = edge-shaped cavity, non-bonded inlay; 3 = round-shaped cavity, bonded inlay; 4 = round-shaped cavity, non-bonded inlay. Adapted from original publication I.

In Study II, it was found that deformation between teeth restored with bonded LDGC and HC occlusal veneers and non-bonded HC veneers was not different. However, deformation of non-bonded LDGC occlusal veneers was considerably inferior compared with the other groups. Chamfer preparation did not influence the deformation of the restored teeth (Figure 13).

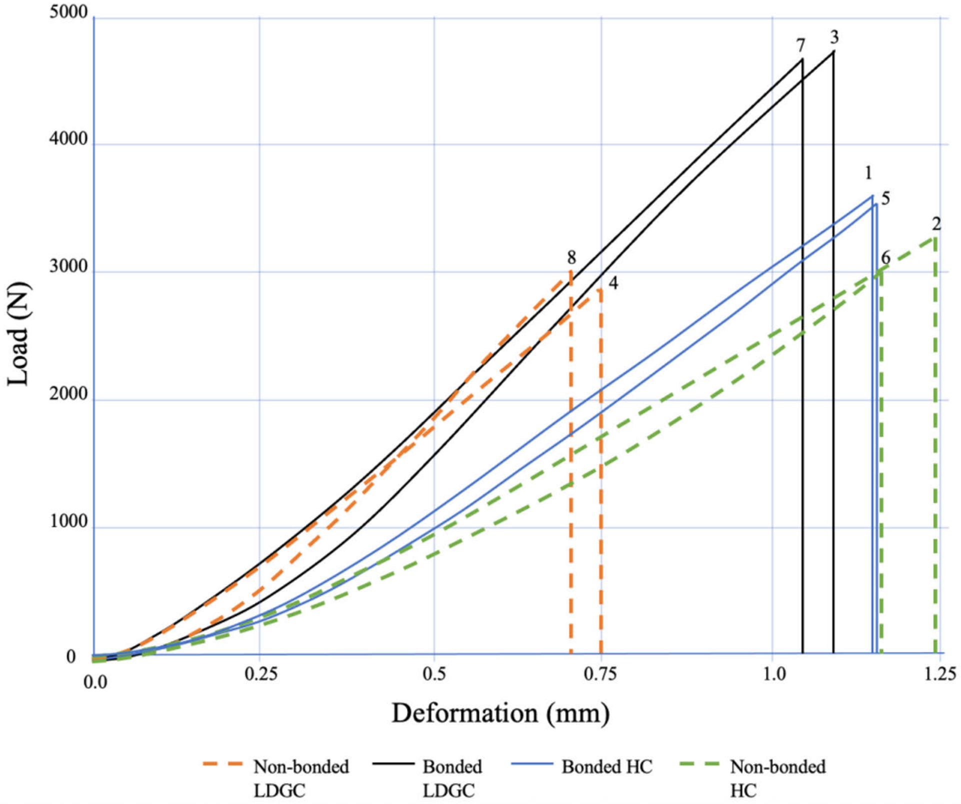


Figure 13. Load-deformation curves in each group in Study II. HC = hybrid ceramic, LDGC = lithium-disilicate glass ceramic. Adapted from original publication II.

Study III exhibited that the type of material and the thicknesses of the occlusal veneer influenced the deformation of the restored tooth. It was found that teeth restored with LDGC occlusal veneers with increased thickness, also showed increased deformation. On the other hand, a clear difference in deformation between groups of teeth restored with HC occlusal veneers was not found. Overall, teeth restored with HC occlusal veneers provided higher deformation compared with teeth restored with LDGC occlusal veneers. The cement layer thickness was not found to influence the deformation of the restored teeth (Figure 14).

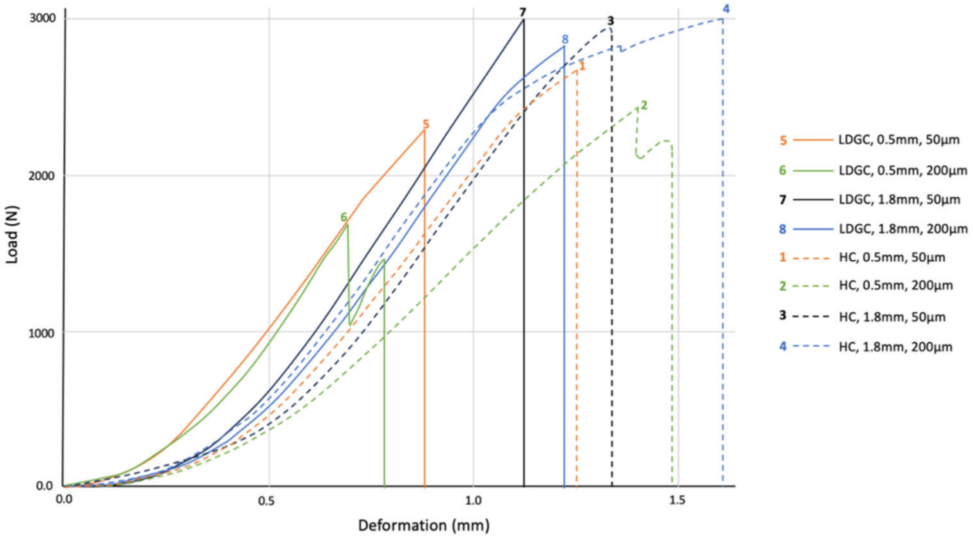


Figure 14. Load-deformation curves according to each group in Study III. HC = hybrid ceramic, LDGC = lithium-disilicate glass ceramic. Adapted from original publication III.

In Study IV, teeth restored with SFRC occlusal veneers presented higher deformation compared with teeth restored with PFC occlusal veneers after 1 day and 6 months of water storage. Also, teeth restored with SFRC occlusal veneers tended to fail gradually after the highest load, whereas teeth restored with PFC occlusal veneers failed instantaneously at the point of the highest load. Although no statistical differences were found in deformation values with the same resin composites, 6 months of water storage slightly increased the deformation of the restored teeth for each material (Figure 15).

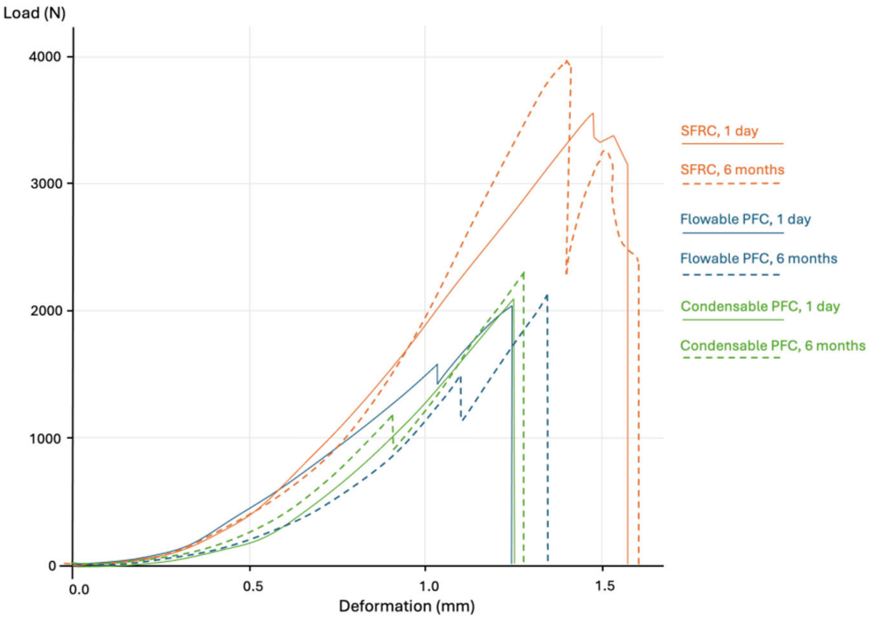
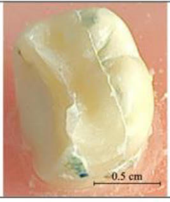
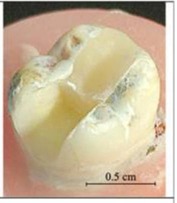


Figure 15. Load-deformation curves for tested restorations. Teeth were stored for 1 day and 6 months in distilled type I water at 37 degrees Celcius. PFC = particulate-filled composite, SFRC = short-fiber-reinforced composite. Adapted from original publication IV.

5.3 Analysis of the Fracture Type (I, II, III, IV)

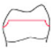
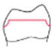
In Study I, all bonded inlays of both cavity designs presented fractures of both the restoration and the tooth, whereas in non-bonded specimens, the majority of the fractures occurred within the inlay. The cavity design did not substantially influence the fracture type (Table 2).

Table 2. Distribution of fracture types in each test group in Study I. Fractures were classified into three types: 1) two-cusps fracture (on the left); 2) one-cusp fracture (middle); 3) inlay fracture (on the right). Adapted from original publication I.

			
Group1: edge-shaped, bonded	11	1	
Group2: edge-shaped, non-bonded	2	3	7
Group3: round-shaped, bonded	8	4	
Group4: round-shaped, non-bonded	1		11

In Study II, fractures of both the occlusal veneer and the tooth were found in teeth restored with bonded occlusal veneers, while in non-bonded occlusal veneers, the veneer loosened without visible fractures of the tooth preparation. Material selection or chamfer preparation was not found to impact the fracture type (Table 3).

Table 3. Fracture type distribution in the test groups in Study II. Red line between tooth preparation and occlusal veneer illustrates non-bonded veneers. Adapted from original publication II.

	Partial tooth fracture	**Complete tooth fracture**	**Loosened restoration**
			
 Group 1, HC	5	3	
 Group 2, HC			8
 Group 3, LDGC	7	1	
 Group 4, LDGC			8
 Group 5, HC	5	3	
 Group 6, HC			8
 Group 7, LDGC	1	7	
 Group 8, LDGC			8

HC = hybrid ceramic, LDGC = lithium-disilicate glass ceramic

In Study III, fracture types were classified as fractured tooth or fractured veneer. In HC occlusal veneers, the majority of the fractures involved tooth fractures. In contrast, 0.5 mm thick LDGC occlusal veneers presented mostly fractured veneers, whereas in 1.8 mm thick LDGC veneers, only restored tooth fractures were visible (Table 4).

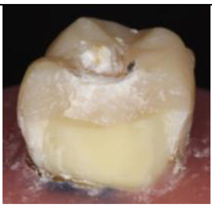
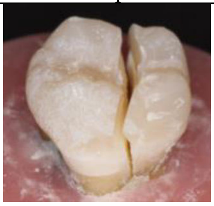
Table 4. Fracture type analysis of the groups in Study III. Adapted from original publication III.

	Fractured tooth 	Fractured veneer 
HC, 0.5mm, 50µm	6/8	2/8
HC, 0.5mm, 200µm	8/8	
HC, 1.8mm, 50µm	7/8	1/8
HC, 1.8mm, 200µm	8/8	
LDGC, 0.5mm, 50µm	1/8	7/8
LDGC, 0.5mm, 200µm	3/8	5/8
LDGC, 1.8mm, 50µm	8/8	
LDGC, 1.8mm, 200µm	8/8	

HC = hybrid ceramic, LDGC = lithium-disilicate glass ceramic.

In Study IV, although the majority of the fractures were catastrophic type, SFRC occlusal veneers presented slightly fewer catastrophic fractures compared with flowable or condensable PFC materials (Table 5).

Table 5. Fracture type analysis with the failure mode presented in percent (%) in Study IV. Adapted from original publication IV.

	Repairable		Non-repairable
			
Flowable PFC 1 day 6 months	30% 40%		70% 60%
SFRC 1 day 6 months	60% 40%		40% 60%
Condensable PFC 1 day 6 months	20% 30%		70% 80%
* Teeth were stored 1 day and 6 months in distilled type I water at 37 degrees Celsius.			

PFC = particulate-filled composite, SFRC = short-fiber-reinforced composite.

5.4 Image Analysis

5.4.1 Scanning Electron Microscopy Micrographs (II, III)

In Study II, SEM micrographs of non-bonded specimens with both HC and LDGC materials displayed wax from the n-hexane wax solution on the bonding surface of occlusal veneers without clear signs of resin cement remnants. In bonded veneer specimens, the bonding surface of the veneer showed a layer of adhesive cement on the surface, demonstrating adhesion of the cement to the veneer in bonded occlusal veneers (Figure 16).

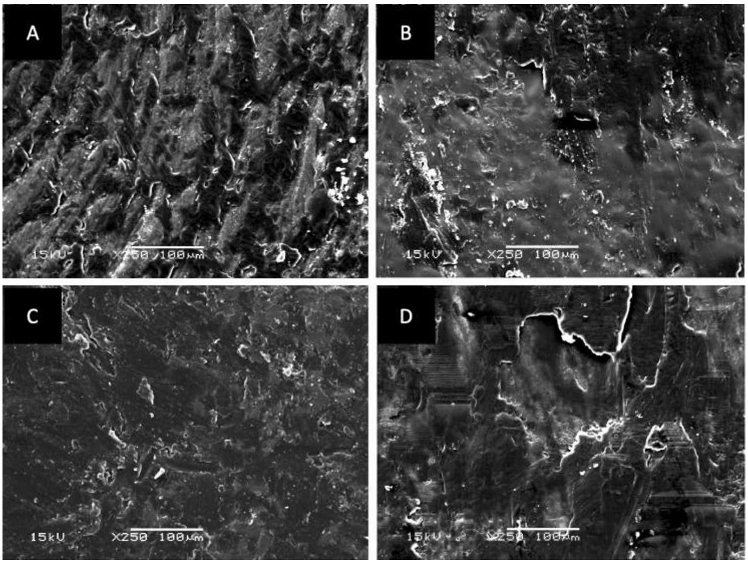


Figure 16. Scanning electron microscopy micrographs of the bonding surface of the veneers after the loading test of Study II. A = Bonded HC, B = Non-bonded HC, C = Bonded LDGC, D = Non-bonded LDGC (original magnification 250x, bar = 100µm). HC = hybrid ceramic, LDGC = lithium-disilicate glass ceramic. Adapted from original publication II.

Analyzing micrographs of Study III, LDGC occlusal veneers seemed to present a smoother fracture surface compared with HC occlusal veneers, which presented a more irregular fracture surface of the occlusal veneers (Figure 17).

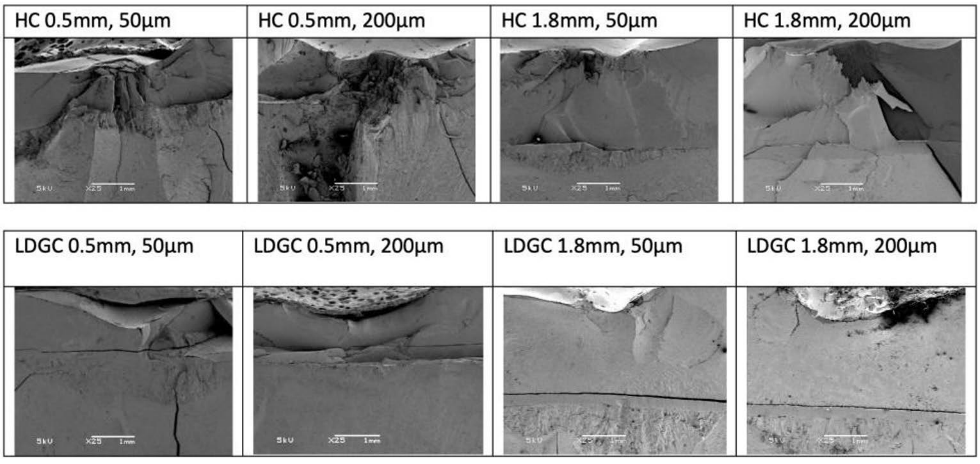

HC 0.5mm, 50µm
HC 0.5mm, 200µm
HC 1.8mm, 50µm
HC 1.8mm, 200µm
LDGC 0.5mm, 50µm
LDGC 0.5mm, 200µm
LDGC 1.8mm, 50µm
LDGC 1.8mm, 200µm

Figure 17. SEM-analysis of the restoration-tooth systems according to each group (magnification 25x, bar = 1 mm). HC = hybrid ceramic, LDGC = lithium-disilicate glass ceramic. Adapted from original publication III.

5.4.2 Micro-computed Tomography Imaging (IV)

In Study IV, visualization of internal voids was enabled by μCT, which revealed different characteristics of internal voids within occlusal veneers between resin composites. Both flowable composites presented small, spherical air bubbles at the superficial layer of the veneers. However, in condensable PFC, irregular voids were located at the lower part of the occlusal veneers (Figures 18 and 19). Condensable PFC presented a statistically significantly higher volumetric ratio of internal voids-to-restorative material (0.26) compared with occlusal veneers made from flowable PFC (0.082) and SFRC (0.095, $p \leq .027$, Figure 18). The Pearson correlation between fracture load and the internal voids-to-restorative material volumetric ratio showed a weak negative correlation between the studied factors, recording -0.065 ($p = .859$), -0.091 ($p = .803$) and -0.199 ($p = .582$) for flowable PFC, SFRC, and condensable PFC, in consecutive order, although no statistically significant differences were found.

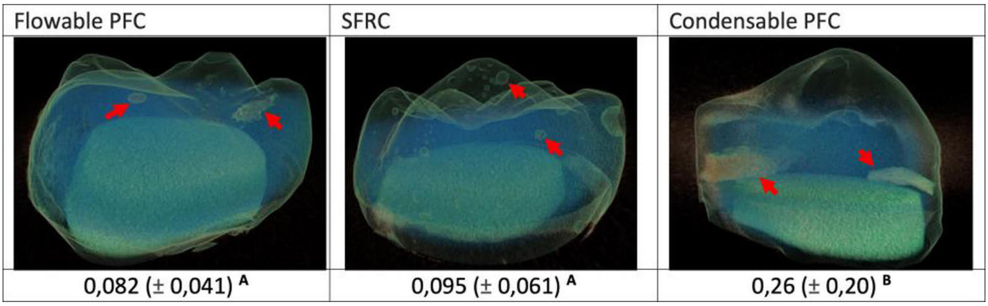


Figure 18. Occlusal veneers scanned with micro-computed tomography (μCT) revealed internal voids within the material indicated by red arrows. Underneath each μCT image presented is the corresponding value of the internal voids-to-restorative material volumetric ratio and standard deviations (in parentheses). Different superscript letters indicate statistically significant difference ($p < .05$). PFC = particulate-filled composite, SFRC = short-fiber-reinforced composite. Adapted from original publication IV.

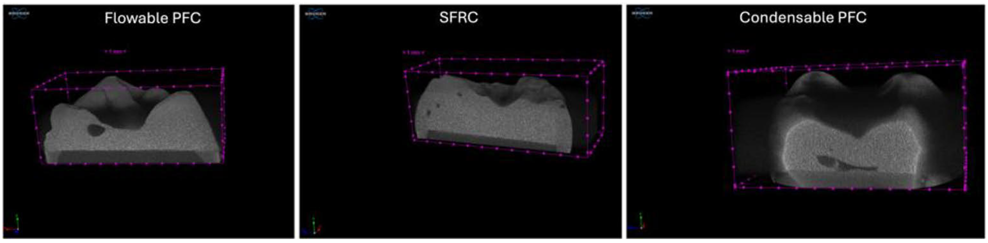


Figure 19. Cross-sectional view of the occlusal veneers scanned with micro-computed tomography (μCT), which revealed internal voids within the material. PFC = particulate-filled composite, SFRC = short-fiber-reinforced composite. Adapted from original publication IV.

6 Discussion

6.1 General Discussion

Novel adhesive restorative materials have rapidly entered the market (Bayne et al., 2019). Simultaneously, tooth wear is a common condition involving 20–45% of permanent dentition (Schlueter and Luka, 2018) for which restorative treatment is occasionally indicated (Loomans et al., 2017). More data about novel indirect and direct materials are needed, especially on how different factors affect fracture load of occlusally restored teeth. For clinicians, it is critical to understand material properties and their possible limitations for successful restorations. As the prevalence of tooth wear is increasing, conservative restorative solutions are needed. The studies in this thesis provide insights to evaluate the mechanical performance of restored tooth by means of quasi-static loading experiments. The results indicated that several factors may influence the fracture load of restored teeth.

Preparation design and the restorative material´s bonding are important when it comes to the strength of a restored tooth. The significance of a rounded internal angle of MOD-cavity on the fracture load of a restored tooth has not been investigated precisely, and hence, it was examined in the first study. Also, bonding of the restoration influences stress distribution of the restored tooth and thus, influence of both MOD preparation design and restoration bonding on fracture load was studied. Study I and Study II focused on the preparation design and restoration´s bonding. In Study III, tooth restored with commonly used indirect HC and LDGC occlusal veneers were evaluated with varying occlusal veneer and cement layer thicknesses. The results suggest that preparation design had no influence on the fracture load of restored teeth. Conversely, restoration bonding increased fracture load and prevented restoration loosening. Both indirect HC and LDGC occlusal veneers ensured high fracture load. However, thin LDGC occlusal veneers recorded lower fracture load and a higher amount of debondings than thick LDGC veneers, while thickness of HC occlusal veneers had no impact on the fracture load or type of fracture. When it comes to direct resin composites, these materials have presented satisfactory clinical performance in the posterior region (Da Rosa Rodolpho et al., 2022). To simulate clinical conditions somewhat better, in Study IV, the fracture load of teeth restored with different direct occlusal veneers was tested after 6 months of water storage. Because injection-moulding technique with flowable resin composite has become common, the selected materials included flowable and condensable PFC, and for the interests of potential future materials in occlusal restorations, flowable SFRC was also studied. The results revealed significant differences in fracture load values between the teeth restored with different direct resin composite occlusal veneers. Teeth restored with direct SFRC occlusal veneers ensured higher fracture load compared with direct PFC occlusal veneers. Water storage duration didn’t influence the fracture load of restored teeth.

There were multiple limitations that must be discussed. Despite careful selection of the collected teeth, slight differences in quality and size of the teeth and disparity in morphology of the restorations created variation in the results. The storage duration of extracted teeth influences the strength of restored teeth. Reportedly, teeth stored in distilled water or distilled water with 0.02% thymol solution dentin permeability increased and bond strength decreased after 6 months (Goodis et al., 1993). Also, teeth stored in deionized water showed decreased surface hardness and elastic modulus of enamel and dentin due to demineralization (Habeliz et al., 2002). As the collected teeth were possibly extracted at different timepoints, the quality of the teeth could have varied. When it comes to the loading test setup, quasi-static loading test did not simulate the impact of repetitive masticatory cycles on the restored tooth. Also, absence of the effect of periodontal ligament in the test setup, which restricts natural movement of the teeth under loading, may decrease value of the study to be transferred directly to clinical practice. However, not only has correlation between static strength and fatigue limits been reported (Bijelic-Donova et al., 2016a), but static loading also unveils information about mechanical stability and fracture behavior of material under loading.

6.2 Influence of Material Selection on Fracture Load of Occlusal Restorations

When analyzing fracture load of the restored tooth, higher fracture load was found in teeth restored with bonded LDGC occlusal veneers compared with non-bonded LDGC or HC veneers. This highlights the importance of well-known bonding properties of glass ceramics and their effect on the durability of the restored tooth (Hallmann et al., 2018). When it comes to bonded veneers, teeth restored with LDGC occlusal veneers recorded either similar or higher fracture load than teeth restored with HC. It has been reported that fatigue and fracture resistance between indirect resin composites and LDGC are comparable (Maldonado et al., 2024). Observing mechanical properties of the used materials, LDGC presents higher flexural modulus (52.8 GPa) and fracture toughness (1.8 megapascals [MPa] $m^{1/2}$), but lower flexural strength (210.2 MPa) compared with the corresponding values of HC (25.0 GPa, 1.2 MPa $m^{1/2}$ and 216.5 MPa, respectively) (Goujat et al., 2018). However, other studies exhibited higher flexural strength in LDGC (376–393 MPa) compared with that of the HC material (194–234 MPa) (Kim et al., 2022, Lawson et al., 2016). When it comes to elastic modulus, LDGC recorded 67 GPa and HC 12 GPa (Lawson et al., 2016). Mechanical properties of materials reflect on the behavior and performance of the restoration under loading. With a high degree of monomer conversion and a high volume of filler particles, indirect HC materials tend to resemble ceramic materials in terms of behavior under loading, although typical properties of resin composites *i.e.* deformation under loading are found. Plasticity of the material is understood to increase resistance to cracks (Leung et al., 2015). Also, HC presents a higher Weibull modulus than LDGC indicating a higher degree of homogeneity and reliability of the HC material (Homaei et al., 2016). Nevertheless, in comparison to the mechanical properties of HC and LDGC, cobalt-chromium presents an elastic modulus of 220 GPa and highly ductile behavior compared with composites and ceramics (Al Jabbari et al., 2014).

When it comes to the fracture load of the teeth restored with direct occlusal veneers, the teeth restored with SFRC occlusal veneers performed the best when compared with the teeth restored with flowable and condensable PFC occlusal veneers. Higher fracture load recorded in the teeth restored with SFRC occlusal veneers demonstrated the reinforcing effect of micrometer-scale glass fibers hindering crack growth during the loading event. It has been shown that with fiber-reinforced composite, fracture toughness is increased by fiber bridging and pull-out mechanisms, which might cause crack arresting and deflection (Bijelic-Donova et al., 2016b, Bijelic-Donova et al., 2022a; Tiu et al., 2020).

In PFCs, filler particles might also cause minor crack´s path deflection, but overall crack hindering mechanisms might be less than in SFRC, which is demonstrated by lower fracture load of teeth restored with PFC occlusal veneers. It is also possible that fibers of the SFRC may have been physically interlocked with the irregularities of the underlying dental substrate and this positively influenced the load bearing capacity. Water storage for 6 months did not adversely influence the fracture load values. In fact, unexpectedly, slightly higher fracture load was recorded with the restored teeth after 6 months of water storage compared with 1 day water storage. This was an interesting finding, because prolonged water storage plasticizes the polymer matrix and reduces flexural strength (Vallittu et al., 2007). Possible degradation of the polymer matrix of the resin composite by the hydrolytic effect of water may take place but it requires considerably longer period and more hostile environments (Leung et al., 2023; Wendler et al., 2021). Higher fracture load found in direct occlusal veneers after 6 months of water storage is possibly due to post-curing or plasticization of the resin matrix of the composite. Slightly plasticized polymer matrix can eliminate stress peak concentration at the interface of the restorative material and tooth substance. Furthermore, resin plasticization might reduce tensile stress and generate compressive stresses at the crack tip, and release stress caused by polymerization shrinkage (Takeshige et al., 2007).

When analyzing the internal voids-to-restorative material volumetric ratio, condensable PFC presented a higher amount of air in the occlusal veneers compared with both flowable materials supposedly due to a difference in application techniques. With condensable PFC, internal voids were located near the bonding surface of the occlusal veneer, whereas with flowable PFC and SFRC, small spherical voids were located mainly at the external surface. However, the difference in application techniques or internal voids didn’t seem to affect fracture load of teeth restored with PFC occlusal veneers. Despite similar fracture loads, a slight negative correlation was found between fracture load and the internal voids-to-restorative material volumetric ratio indicating a weakening effect of internal voids on fracture load of occlusal veneers, although the correlations were not statistically significant.

With indirect resin composites, control of polymerization shrinkage and a better cured resin matrix might lead to advantageous restorative solutions compared with direct resin composites (Dalpino et al., 2002). When comparing fracture load of teeth restored with direct PFCs and indirect HC used in this study, indirect HC presented higher fracture load, although all direct occlusal veneers exceeded the mean maximal bite force in the molar region, reportedly 909 N (Waltimo and Könönen, 1995). Indirect HC contained 71 wt% of filler particles, while the corresponding filler loading was 69 wt% for flowable PFC and 81 wt% for condensable PFC. Interestingly, flowable and condensable PFCs recorded similar fracture load values. Thus, higher fracture load is assumed to be due to the degree of monomer conversion, as indirect resin composites have higher monomer conversion than direct resin composites. Degree of monomer conversion of 2 mm thick microhybrid and nanofilled direct resin composite has been reported to be approximately 55–70% after 40 seconds of curing with 600–1000 mW/cm^2 (Galvão et al., 2013; Ribeiro et al., 2012). With indirect restorations, a higher degree of monomer conversion is obtained in a controlled polymerization environment with high temperature and pressure. Nevertheless, it's noteworthy that longevity of direct and indirect restorations might not be different and direct restorative technique might ensure a more conservative restorative approach (Opdam et al., 2016). Interestingly, when comparing the fracture load of teeth restored with direct SFRC occlusal veneers in Study IV and teeth restored with indirect occlusal veneers in studies II–III, teeth restored with SFRC occlusal veneers presented either comparable or higher fracture load than teeth restored with HC veneers. When comparing teeth restored with SFRC and LDGC occlusal veneers, the fracture load of teeth restored with SFRC occlusal veneers might not be inferior. Consequently, direct SFRC occlusal veneers might provide a conservative and long-lasting solution for posterior occlusal restorations in terms of fracture load. However, the use of SFRC on the occlusal surface is not yet instructed because of lack of some preclinical and clinical data.

Controversial findings have been reported regarding the thickness of restorative materials on tooth substance. With occlusal veneers at thicknesses of 0.5 mm and 1.0 mm, both indirect HC and LDGC have recorded sufficient fracture load for the posterior region (Ioannidis et al., 2019). Zimmermann et al. (2019) studied minimal thickness (0.5 mm, 1.0 mm, 1.5 mm) of crowns finding that resin composite crowns recorded higher fracture load compared with LDGC crowns after thermodynamic loading followed by loading until fracture. These findings are supported by the results of the Study III, as teeth restored with 0.5 mm thin HC occlusal veneers provided higher fracture load compared with teeth restored with LDGC veneers. These reports suggest the use of resin composite materials as a favorable option when it comes to thin restorations. In contrast, Al-Akhali et al. (2017) reported that LDGC presented higher fracture load of occlusal veneers with cusp/fissure thickness of 0.5/0.8 using quasi-static loading test after thermodynamic loading. When it comes to thickness of 0.5–0.6 mm, both indirect resin composite and LDGC veneers could provide a sufficient option for restoring worn posterior teeth (Maldonado et al., 2024). Due to controversial findings, more studies are needed on materials used for thin occlusal veneers, although findings in the existing literature and the fracture load values recorded in Study III of this thesis support using HC occlusal veneers in lower thicknesses than LDGC occlusal veneers. Furthermore, it must be mentioned that bonding characteristics toward both dentin/enamel and toward the restorative material could affect the success of restorations. Rocca et al. (2021) found that the bonding substrate might influence the fracture load of thin (0.5–1.5 mm) indirect resin composite restorations, but not on the fracture load of 2.0 mm thick restorations and the load-bearing capacity linearly increased with increase in restoration thickness. It’s also important to consider that in clinical situations, fatigue resistance of the material is an important parameter, as clinically materials tend to fail below the maximum strength by relatively low, repeated cyclic loading rather than under a single high load (Özcan et al., 2018). When it comes to fatigue resistance, direct and indirect resin composites and LDGC have presented satisfactory values (Belli et al., 2014; Maldonado et al., 2024). While lithium-disilicate crystals deflect and branch cracks, preventing crack from propagating through glass matrix, in resin composites, a high degree of conversion and filler content by volume are thought to resist crack propagation (Belli et al., 2014).

According to Study III, differences in cement layer thickness on fracture load were not found to be an important factor for HC material. In contrast, fracture load was reduced with 0.5 mm thick LDGC occlusal veneers when the cement layer thickness was increased to 200 µm. Correspondingly, Rojpaibool and Leevailoj (2017) found that increasing the cement layer thickness from 100 µm to 300 µm fracture load of 1 mm thick LDGC plate was reduced. However, opposing findings have been reported, when the effect of varying cement layer thicknesses (100, 200, and 300 µm) on the fracture load of 1 mm and 2 mm thick ceramic plates was studied. It was found that with 1 mm thick ceramic plate luted to dentin, increasing the cement layer thickness gradually increased the fracture load, which was not the case with 2 mm thick ceramic plates (Prakki et al., 2007). This partly supported the findings of the Study III, in which the fracture load was not considerably affected by cement layer thickness when 1.8 mm thick occlusal veneers were tested. The results from Study III suggest that when a tooth is restored, both the thickness and the mechanical properties of the restorative material and cement should be considered. However, more research needs to be conducted on cement layer thickness, especially when thin restorations are considered.

6.3 Stress Distribution of Restored Tooth

Material microstructure is a major factor that determines stress distribution and behavior during tooth loading. When considering the stress applied to a tooth, it's important to take into account the resiliency of the periodontal ligament. The mobility of a tooth can increase due to periodontal disease, which means that occlusal stress may not reach high levels since the tooth can shift under the occlusal pressure. When it comes to LDGC occlusal veneers, more stress is concentrated within the restorative material, while resin composite materials deform and dissipate energy before fracture (Niem et al., 2019). This was shown in studies II and III by load-deformation curves recorded during loading, in which teeth restored with bonded 1.8 mm thick LDGC occlusal veneers revealed lower deformation compared with indirect HC occlusal veneers. Also, with non-bonded veneers, HC recorded higher deformation compared with LDGC, although the restoration loosened under similar load with both materials. When 0.5 mm thick veneers were studied, stress got transmitted from the HC occlusal veneer to the tooth structure, whereas with LDGC occlusal veneers, stress might have concentrated within the veneer and cement layer, causing fracture of the occlusal veneer, demonstrating the importance of LDGC veneer thickness on the load-bearing capacity of a restored tooth. In fact, a similar finding has been reported also with 0.5 mm thick CAD/CAM resin composite overlays bonded to enamel and dentin, suggesting that enamel, with a higher elastic modulus than dentin, could absorb stresses and resist bending of the underlying tooth structure (Rocca et al., 2021). However, when CAD/CAM resin composite overlays were bonded to dentin only, debondings became the apparent failure type (Rocca et al., 2021). Stress distribution might also influence fracture type, and it was found that with LDGC occlusal veneers, teeth restored with bonded 1.8 mm thick veneers presented tooth and restoration fractures. This could be due to a sufficient thickness of the LDGC occlusal veneer resisting flexural deformation of the occlusal veneer. This finding might indicate that during loading of 1.8 mm thick LDGC occlusal veneers, stress from occlusal contact area dissipates from the occlusal veneer, initiating a fracture which propagates downwards to the restored tooth structure without occlusal veneer debondings. However, when 1.8 mm thick LDGC veneers were non-bonded, restorations loosened without visible fractures in the tooth structure, demonstrating the importance of bonding for stress transfer from the occlusal veneer to the tooth preparation. The prerequisite of bonding of the glass ceramic is therefore of paramount importance for a successful ceramic restoration. Typically, due to tensile stresses caused by bending of the ceramic against a less stiff substrate, fracture initiates from the internal surface of ceramic crowns (Kelly et al., 2010).

When it comes to stress distribution in restored tooth, cement layer needs to be considered. FEA analysis has indicated that when a thick restoration and a high elastic modulus restorative material are used, stress in the cement layer decreases, which might be due to lower deformation of the material (Zhu et al., 2017). Correspondingly, Study III showed that the influence of cement layer thickness on the fracture load of restored tooth was dependent on the occlusal veneer material. According to an FEA analysis and an *in vitro* study, a thicker resin cement layer resulted in lower fracture load, possibly due to polymerization shrinkage and the lower elastic modulus of resin cement than ceramic material (May et al., 2012; Rojpaibool and Leevailoj, 2017). Overall, in teeth restored with LDGC occlusal veneers, stress has been reported to concentrate within the veneer, reducing the stress in the cement layer, whereas with HC material, stress peaks were recorded in the cement layer instead of the occlusal veneer due to lower elastic modulus (Tribst et al., 2018). Also, considering a conservative cavity preparation, it’s important to keep in mind that with a reduced thickness of the restoration, strain values at the cement layer increase and the restoration is prone to debonding (Zhu et al., 2017). This might explain the fracture load values and fracture types found in Study III, as HC occlusal veneer could transmit stress to the underlying cement layer and tooth structure through deformation during loading. However, with 0.5 mm thick LDGC occlusal veneers, debondings were observed as the main failure mode, which indicate that the difference in mechanical properties of the ceramic and the resin cement should be emphasized when a 0.5 mm thin ceramic occlusal veneer is used, especially with a 200 µm thick cement layer.

Another factor that could affect stress distribution of restored tooth is preparation design, which needs to be taken into consideration with indirect restorations. Study I demonstrated that for increased fracture load, a rounded MOD-cavity design is recommended over an edge-shaped design, although the difference in fracture load was not statistically significant. With the rounded design, higher fracture load indicates that stress is distributed over a larger area compared with the edge-shaped design. High stress peaks are typically located in the sharp edges of preparation (Couegnat et al., 2006). Thus, with an optimal preparation design, the strength of the restored tooth is increased (Ahlers et al., 2009). When it comes to occlusal veneers, chamfer preparation could have a favorable effect on fracture load after fatigue simulation by resisting shear stresses (Taha and Hafez, 2024). Increased fracture load under oblique loading of adhesive CAD/CAM crowns with a 2–4 mm axial wall height was found compared with a 0 mm or 1 mm axial wall height of the crown, which could demonstrate the limited ability of adhesive technology to compensate for extensive preparation (Hoopes et al., 2018). This was not the case in Study II, perhaps due to a different loading test setup, as considerable stress concentrations could have not been in the marginal area of the restorations (Clausen et al., 2010). Nevertheless, in a 3-year clinical trial, Schlichting et al. (2022) presented promising performance of minimally invasive occlusal veneers without chamfer preparation. Also, various extensive preparation types might not increase fracture load according to a systematic review of *in vitro* studies (Sirous et al., 2022). Non-retentive indirect partial ceramic crowns have presented promising clinical performance also in long-term studies, which supports the use of minimally invasive restorations (Arnetzyl and Arnetzyl, 2012; Belleflamme et al., 2017; Guess et al., 2013b).

Mechanical performance of direct PFC in terms of fracture toughness, elastic modulus, and flexural strength is determined by its microstructure, including filler particles, resin monomer composition, and degree of monomer conversion (Ilie, 2021). Increasing filler load and decreasing the size of filler particles relate to higher mechanical properties of PFC (Shen et al., 2020). However, in Study IV, load-deformation curves and fracture types were not different between flowable and condensable PFC, indicating similar behavior under loading despite the differences in the size and volume of filler particles: flowable PFC included 69 wt% of 150 nm sized spherical filler particles and condensable PFC 81 wt% of pre-polymerized micrometer and nanometer sized filler particles. This agrees with the findings of earlier literature, which investigated fracture behavior and mechanical properties of crowns made from the same PFCs and SFRC which were used in Study IV. It was shown that flowable and condensable PFC crowns presented similar load-bearing capacity (Lassila et al., 2020). Also, when addressing fracture toughness and flexural strength, similar values were presented for the resin composites used in Study IV (Lassila et al., 2020). Behavior under loading seemed to be similar even after 6 months of water storage in Study IV. Despite a minor increasing effect of water sorption on fracture load and deformation found in the Study IV of this thesis, a crack could rapidly propagate through the material if it has reached the critical crack size, and under aqueous environment, crack growth is accelerated (Takeshige et al., 2007).

SFRC has presented not only significantly higher fracture load and fracture toughness but also slightly higher flexural strength than that of the PFC materials tested (Lassila et al. 2020). Correspondingly to the findings of Study IV, besides the reinforcing effect of fibers, a favorable fracture type has been reported with uncovered SFRC restorations (Jakab et al., 2024). Propagation of a crack in SFRC occlusal veneers is arrested by fiber bridging and pull-out mechanisms, which might be detected in load-deformation curves, in which the ultimate failure of SFRC veneers did not occur at the highest loading point. This could influence a less destructive fracture type, as fibers might guide crack propagation towards the peripheries of the restoration (Jakab et al., 2024). However, it’s noteworthy that statistically significant differences in fracture types between SFRC and PFC were not observed in Study IV.

6.4 Clinical Considerations and Perspectives of Future Studies

Multiple clinical studies of direct and indirect posterior occlusal restorations have been conducted. When comparing direct resin composite and indirect ceramic restorations for patients with severe tooth wear after 5 years, the survival rate for direct resin composite and indirect LDGC restorations was 86.3% and 93.1%, respectively (Cascales et al., 2023). As a cusp-replacing restoration, direct and indirect resin composite restorations for premolars revealed no statistically significant difference in survival rates, 89.9% and 83.2%, respectively, after a 5-year follow-up (Fennis et al., 2014), which was slightly lower compared with a study of equivalent follow-up time, showing success rates of 97.5% and 98.4% for posterior direct and indirect resin composite restorations, respectively (Cetin et al., 2013). When it comes to a 3-year clinical trial, ultrathin (thickness of 0.4–0.6 mm in the central groove, 1.0–1.3 mm at the cusps) CAD/CAM resin composite and LDGC posterior occlusal veneers provided survival rates of 84.7% and 100% in consecutive order (Schlichting et al., 2022). These findings are in line with a study by Edelhoff et al. (2019), who studied 103 pressed full-mouth LDGC occlusal onlays with a minimal thickness of 1 mm in patients with severe tooth wear, recording a survival rate of 100% after a mean follow-up duration of 8 years. Also, for HC, molar restorations with a mean thickness of 0.55 mm revealed a survival rate of 100% and a success rate of 93.5% after 2 years (Oudkerk et al., 2020), which was slightly higher compared with 1.0–1.5 mm thick partial coverage HC restorations after 3 years, presenting a survival rate of 97.5% (Spitznagel et al., 2018). In a 1–3-year follow-up study, posterior LDGC partial coverage restorations slightly outperformed HC counterparts in terms of restoration failure and loss of retention (Prott et al., 2024). When it comes to cracked teeth with pain symptoms, LDGC occlusal veneers might be a beneficial option, as found in a 22-month follow-up study presenting a 92.6% success rate (Zhao et al., 2024).

For successful and long-lasting restorations, it's fundamental to understand the properties of the used material and restored tooth structure. More long-term clinical studies are needed to validate short-term clinical results, especially when it comes to conservative tooth preparation and thin occlusal veneers, to understand the materials and their limitations for posterior occlusal restorations. Also, as more conservative restorations are evaluated, it should be emphasized that cement layer thickness may have a significant influence on the performance of the restored tooth. Direct restorations could also be a beneficial option for restoring worn teeth. An interesting concept for future studies could also include SFRC occlusal restorations, as the SFRC base design of the restoration and uncovered proximal SFRC restorations have presented promising performance in laboratory studies and recent mid-term clinical studies too (Bijelic-Donova et al., 2022b; Garoushi et al., 2012; ElAziz et al., 2024). However, more laboratory-based studies using a cyclic loading test setup are needed, where continuous repetitive load is applied on the restored tooth, simulating oral masticatory forces.

7 Conclusions

Based on the findings of the acquired data from these *in vitro* laboratory studies, the following conclusions can be drawn:

1. Bonding of inlay and occlusal veneer restorations influence more on the fracture load of the restored teeth than the design of the preparation.

2. Teeth restored with LDGC occlusal veneers have similar or higher fracture load compared with teeth restored with HC occlusal veneers.

3. Thin occlusal veneers made of HC material are not as sensitive to variations of cement layer thickness than thin occlusal veneers made of LDGC.

4. Teeth restored with direct SFRC occlusal veneers have a higher fracture load compared with teeth restored with flowable or condensable PFC veneers.

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