Doctoral Dissertation
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Evaluation of fiber enriched composite resin for adhesive tooth restoration

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Summary

The subject of the present thesis is the capacity of glass fiber to improve mechanical properties of dental resin composites.
Nowadays composite resins reached a fast development even if they still show some limits in term of mechanical properties.
During masticatory cycle there is a slow and repetitive cycling loading, which decreases the strength of particulate filler composite resins (PFCs) that, in case of big restoration, could bring to a fracture of the restored teeth. For this reason, there is an increment in the use of resin composite but in case of large dental tissue loss, prosthetic solution was still preferred. Thus, in recent years, the incorporations of fibers inside composites has been introduced in order to improve properties and clinical application of these materials.

Fiber Reinforced Composite (FRC) can be used in higher stressed areas because have better flexural strength properties than commercial composite. Moreover, thanks to their silane preimpregnation, have better control on the polymerization-shrinkage stress. This could decrease interfacial gap formation and the probability of failure of the restorations.

The present series of experiments aimed to investigate the mechanical properties of fiber reinforced composites and their possible application to direct restorations. In particular, FRC were tested to determine their effect on flexural strength, on the marginal adaptation and the fracture resistance if applied on direct composite restorations of endodontically treated teeth, which represent one of the most critical clinical condition to deal with.
Based on the studies included in this thesis, the following conclusions were drawn:

- The use of glass fiber inserted horizontally within a direct composite restoration didn’t show a significant increment in mechanical properties. In particular, flexural strength and fracture toughness test didn’t show any increase when horizontal fibers were used.
- The insertion of horizontal glass-fibers seemed to reduce marginal gap after cyclic loading
- Fractographic analysis showed that glass fibers with a buccal-palatal orientation partially deviated fracture, even if it did not prevent catastrophic fracture of the specimens.
- The use of short fiber resin composite for direct restorations of endodontically treated teeth significantly improved fracture resistance if specimens were immediately loaded until fracture.
- Cyclic loading induced a decrement of fracture resistance of direct composite restorations with fibers.

- Fractographic analysis of short glass fiber samples seemed to show more reparable fracture patter in comparison with commercial direct restoration. However, further studies are necessary to verify the fracture pattern with standardized occlusal loading.

Further studies are needed to evaluate Fiber Reinforced Composite behavior on marginal gap and fracture pattern, considering the anatomy of the occlusal surface and the design of the cavity margin.

Contents

Capter1:Introduction

1.1 Composite materials

The precursor of resin-based composite materials were acrylic resins, particularly polymethyl-methacrylate (PMMA), which was introduced to the dental profession in 1936 as Vernonite and was employed for inlays, crowns and fixed partial dentures [Rueggeberg 2002]. However, the use of PMMA-based restorations was limited due to several factors: volumetric shrinkage during polymerization, a large difference in the thermal expansion coefficient between PMMAs and the surrounding tooth, color instability, poor adhesion and marginal leakage. As a consequence of these limitations a high incidence of marginal staining and recurrent caries was identified at the restoration/tooth interface [Paffenbarger et al. 1953; Rueggeberg, 2002].

Bowen in the 1950s developed novel organic high molecular weight epoxy resin and methacrylate derivatives that incorporated inorganic filler particles and sought to reduce the detrimental polymerization shrinkage of the preceding PMMAs. This work resulted in a patent in 1958 of a material composed of 75% by weight of quartz or aluminosilicate glass filler and 25% by weight polymerizable resin monomer, namely the dimethacrylate formulation 2,2-bis [4-(2-hydroxy-3-methacryloxypropoxy)phenyl] propane (bisphenol-A glycidyl methacrylate; BisGMA). Subsequently, the large molecular size and chemical structure of the bifunctional BisGMA resulted in decreased polymerization shrinkage compared with PMMAs and improved the elastic modulus, tensile and compressive strengths [Bowen 1956].

The high viscosity of BisGMA limited the filler particle loading necessitating the introduction of a lower molecular weight monomer, namely triethylene glycol dimethacrylate (TEGDMA) to reduce the viscosity of the paste and allow for increased filler loading and appropriate handling characteristics. A silane-coupling agent was used to coat the glass filler particles prior to incorporation into the resin matrix to promote adhesion between the glass filler and the BisGMA/TEGDMA co-monomer [Rueggeberg 2002].

Early composite resins were chemically cured via a reduction-oxidation reaction to initiate free radical polymerization [Bowen 1956; Bowen 1958; Bowen & Rodriguez 1962; Bowen RL.

1964]. As composite resins were developed, light-activated polymerization was introduced and subsequently a photo-initiator, such as camphoroquinone, was added to promote the curing reaction, whilst the addition of an inhibitor, such as hydroquinone, was also required to increase both the shelf-life of the material and working time available to the dental practitioner during placement [Rueggeberg, 2002]. UV lights were first used but had a limited depth of cure due to their low power light sources. The development of catalysts triggered by visible light solved this problem and allowed greater depth of polymerization compared with UV light [Rueggeberg, 2002; Minguez et al., 2003]. One of the main advantages of light activated materials was that it increased working time for the dentist, allowing the placement of the material inside the cavity through appropriate layering technique before exposure to the light and initiation of the polymerization reaction [Rueggeberg, 2011].

Classification of resin based composites

Many classifications have been proposed over years. To date, dental composite materials are commonly classified according to the mean size of the inorganic filler particles or volume percent of filler [Lang et al.1992; Willems et al.1992]. The first classification system was based on the mean size of filler particles, manufacturing techniques and chemical composition of the filler [Lutz & Philips 1983]. The classification of composites according to filler type has produced a wide variety of classifications and sub-classifications as new materials have been developed and existing ones refined, although the system developed by Lutz & Philips [Lutz & Philips 1983] remains the most widely accepted.

Macro-filled Composites

Macro-filled composites, also referred to as conventional or traditional composites, are constituted by large reinforcement particles, being that the more common materials used are finely ground amorphous silica and quartz. These composites contain glass filler particles with average particle size of 10 µm to 20 µm and the largest particles of 50 µm, and are characterized by a wide distribution in particle size. Inorganic filler loading ranges from: 70% to 80% in weight or 60% to 70% in volume. Due to the inclusion of such large particles surface finishing is poor and in sliding contact, resin could be removed along with these protruding filler particles [Lutz & Philips 1983].

Micro-filled Composites

Micro-filled composites contain silica particles in the range 0.01 µm−0.1 µm with a typical average particle dimension of 0.04 µm (40 nm). This value is one-tenth of the wavelength of visible light and 200 to 300 times smaller than the average particles in macro-filled composites. Due to average particle sizes these composites exhibit smooth surfaces very similar to that obtained for unfilled acrylic resins. Colloidal silica particles tend to agglomerate during mixing, agglomerates account for particle sizes ranging from 0.04 µm to 0.4 µm. The very small particle size produces a massive increase in available surface area for a given volume of filler (typically 103 − 104 times more surface area). Consequently, it is not possible to incorporate very high filler loadings for small particle size. The available products contain only 30%−60% filler by weight. Even at these lower levels, calculations show that many filler particles must be present as agglomerates and not as individual particles surrounded by resin [Fugolin & Pfeifer 2017].

Hybrid Composites

Hybrid composites combine the features, and particularly the advantages of both micro-filled and macro-filled composites. Hybrid composites cover a broad range of particle sizes. This wide range of particle sizes may cause high filler loading with resultant high strength. Typically, hybrid composites contain filler with an average particle size of 15- 20 µm and 0.01- 0.05µm [Fugolin & Pfeifer 2017].

Nano-filled Composites

Nanotechnology has led to the development of a new resin composite. This is characterized by the inclusion of nanoparticles, 20 or 75 nm in size, and nano-aggregates of approximately 0.6-1.4 µm, which are made up of zirconium/silica or nanosilica particles. In order to ensure that the aggregates bind to the resin, they are treated with silane. The distribution of the filler, aggregates and nanoparticles gives a high load, up to 75% in weight.

Nano-composites are available also as nano-hybrid types. An increased filler load is achieved from the reduced dimensions of the particles, along with their wide size distribution. This consequently reduces the polymerization shrinkage and increases the mechanical properties, such as tensile strength, compressive strength and fracture resistance. These characteristics are higher than those of conventional composites and significantly superior to those of micro-filled composites [Beun et al 2007, Kim et al 2002].

The presence of nano-sized filler particles in composite materials have been identified to produce distinct improvements to the material itself, such as increased filler loading in hybrid-type materials as nano-sized particles pack more efficiently between larger particles and also a subsequent reduction in polymerization shrinkage [Mitra & Holmes, 2003]. An extensive study conducted by Beun et al. (2007) compared the flexural strength, elastic modulus, Vickers microhardness and degree of conversion of several nanofills with universal and microfilled composites. The study concluded that the nanofills Filtek™ Supreme (3M ESPE) and Grandio (Voco) exhibited superior flexure strengths, surface hardness values and elastic moduli compared with the other Composites tested, with the exception of Filtek™ Z100 (3M ESPE). Subsequently, both nanofilled materials were indicated for posterior and anterior placement [Beun et al., 2007].

Later, Randolph et al. showed that mechanical properties of dental resin-based composites (RBCs) are highly dependent on filler characteristics (size, content, geometry, composition). Based on these results, they classified RCBs based on the filler content and using two levels: 50 and 74 vol%. The terms ultra-low fill, low-fill and compact resin composites would apply to materials with filler contents lower or higher than 50 vol% or higher than 74 vol%, respectively.

The addition of even small quantities of nano-sized silica particles has been identified to improve the mechanical properties. Tian et al. (2008) highlighted that the addition of 1 and 2.5% mass of nano-sized fibrillar silica to a BisGMA/TEGDMA resin significantly improved the flexure strengths (128 and 130MPa) compared with conventionally filled composites, (110 and 120 MPa respectively). This was suggested to occur as a consequence of the reinforcing effect of highly separated and uniformly distributed nano-fibrillar silica, whilst the formation of agglomerates of fibrillar silica may weaken the resulting material [Tian et al. 2008]. Nanoparticles produce a more homogeneous filler distribution in low viscosity materials, such as bonding agents. The incorporation of nanosized filler in bonding agents also produced a more structured bond at the tooth/bonding agent interface as filler penetrates the dentine tubules to reinforce the hybrid zone [Breschi et al. 2008].

A further phenomenon contributing to the aesthetic appearance of nanofilled composites was that such materials appear translucent as a consequence of the small size of the dispersed nano-sized filler particles [Mitra & Holmes, 2003]. This occurs as the particle size is smaller than the wavelength of incident light (400-700nm), the subsequent scattering coefficient is reduced enabling light to pass through the material without refraction at the interface between the resin matrix and inclusions, such as filler particles and porosity voids [Ruyter & Oysaed 1982; Lee 2007].

Modern micro- and nano-filled have also been described as ‘universal’ or ‘all-purpose’ composites and have been indicated for both anterior and posterior placement [Cobb et al 2000; Manhart et al 2001]. Universal composites possess appropriate filler distributions to attain a maximum loading in excess of 80% in weight with a non-uniform size distribution of less than or equal to 1μm, providing flexural strengths of up to 160 MPa [Lohbauer et al. 2006; Lu et al 2006]. In addition, Cobb et al. (2000) identified that universal composites exhibited an increased resistance to wear and improved surface polishing compared with preceding materials. [Cobb et al. 2000]

References

Beun S, Glorieux T, Devaux J, Vreven J, Leloup G. Characterization of nanofilled compared to universal and microfilled composites. Dent Mater. 2007 Jan;23(1):51-9.

Bowen RL. Use of epoxy resins in restorative materials. Journal of Dental Research, 1956; 35: 360-369

Bowen RL. Synthesis of a silica-resin direct filling material: progress report. Journal of Dental Research, 1958; 37: 90-91.

Bowen, R.L and Rodriguez, M.S. Tensile strength and modulus of elasticity of tooth structure and several restorative materials. Journal of the American Dental Association, 1962; 64: 378-387.

Bowen RL. Effect of particle shape and size distribution in a reinforced polymer. Journal of the American Dental Association, 1964; 66: 57-65

Breschi L, Mazzoni A, Ruggeri A, Cadenaro M, Di Lenarda R, De Stefano Dorigo E. Dental adhesion review: aging and stability of the bonded interface. Dent Mater. 2008 Jan;24(1):90-101.

Cobb DS, MacGregor KM, Vargas MA, Denehy GE. The physical properties of packable and conventional posterior resin-based composites: a comparison. J Am Dent Assoc. 2000 Nov;131(11):1610-5.

Fugolin APP, Pfeifer CS. New Resins for Dental Composites. J Dent Res. 2017 Sep;96(10):1085-1091. doi: 10.1177/0022034517720658. Epub 2017 Jul 21. Review.

Kim KH, Ong JL, Okuno O. The effect of filler loading and morphology on the mechanical properties of contemporary composites. J Prosthet Dent. 2002 Jun;87(6):642-9.

Lang BR, Jaarda M and Wang RF. Filler particle size and composite resin classification systems. Journal of Oral Rehabilitation, 1992; 19: 569-584

Lee YK. Influence of scattering/absorption characteristics on the color of resin composites. Dent Mater. 2007 Jan;23(1):124-31.

Lohbauer U, Frankenberger R, Krämer N, Petschelt A. Strength and fatigue performance versus filler fraction of different types of direct dental restoratives. J Biomed Mater Res B Appl Biomater. 2006 Jan;76(1):114-20.

Lu H, Lee YK, Oguri M, Powers JM. Properties of a dental resin composite with a spherical inorganic filler. Oper Dent. 2006 Nov-Dec;31(6):734-40.

Lutz F and Philips RW. A classification and evaluation of composite resin systems. Journal of Prosthetic Dentistry, 1983; 50: 480-488.

Manhart J, Chen HY, Hickel R. The suitability of packable resin-based composites for posterior restorations. J Am Dent Assoc. 2001 May;132(5):639-45.

Minguez N, Ellacuria J, Soler JI, Triana R, Ibaseta G. Advances in the history of composite resins. J Hist Dent. 2003 Nov;51(3):103-5

Mitra SB, WU D, Holmes BN. An application of nanotechnology in advanced dental materials. J Am Dent Assoc 2003;134:1382–90

Paffenbarger GC, Nelsen RJ and Sweeney WT. Direct and indirect filling resins: a review of some physical and chemical properties. Journal of the American Dental Association, 1953; 47: 516-524.

Rueggeberg FA. From vulcanite to vinyl, a history of resins in restorative dentistry. Journal of Prosthetic Dentistry, 2002; 87: 364-379.

Rueggeberg FA. State-of-the-art: dental photocuring--a review. Dent Mater. 2011 Jan;27(1):39-52.

Ruyter IE, Oysaed H. Conversion in different depths of ultraviolet and visible light activated composite materials. Acta Odontol Scand. 1982;40(3):179-92.

Tian M, Gao Y, Liu Y, Liao Y, Hedin NE, Fong H. Fabrication and evaluation of Bis-GMA/TEGDMA dental resins/composites containing nano fibrillar silicate. Dent Mater. 2008 Feb;24(2):235-43.

Willems G, Lambrechts P, Braem M, Celis JP and Vanherle G. A classification of dental composites according to their morphology and mechanical characteristics. Dental Materials, 1992; 8: 310-319.

1.2 Bulk-fill resin composites

The early years of composite resins created challenges because of material composition, bonding, layering, curing, finishing and polishing techniques. After years of development a predictable success with composite restorations could be achieved [Manhart et al 2004]. There have been many advances to composite resins in terms of strength, shrinkage, polishability, durability and esthetics. However, for most resin-based materials, a methodical layering technique is strictly required for success, above all in high C-factor cavities [Kwon et al 2012, van Dijken 2010].

In some direct composite restorations, the use of a horizontal flowable composite layer on dentin has been suggested, due to its greater ability to internal flow and adaptation which partially compensates shrinkage stress, thus going to be an "elastic layer" between the substrate and the restorative material [Aggarwal et al. 2014; Oliveira et al. 2010]. To be successful with closed/open sandwich technique, the flowable composite resin should have certain properties that will guarantee an adequate long-term performance. The use of flowable composite in the high C-Factor cavities below the composite ensures a better marginal integrity [Chuang et al 2004] and reduced enamel fracture [Haak et al 2003]. It also improves the fit between adhesive system and composite material decreasing voids [Campos et al. 2014].

Recently, with the attempt to overcome some composite limitations, a new type of light-curing resin composite have been introduced, the so-called bulk fill resin composites, which can present low and high viscosity. These materials should present an increased maximum increment thickness and thus could be placed in layers up to 4 mm thick without compromising the polymerization and the degree conversion [Czasch & Ilie 2013; Ilie et al. 2013a], resulting in a need for fewer increments. In any case, the bulk-fill flowable composite should be covered with at least a 2 mm layer of conventional composite [Burgess & Cakir 2010; Roggendorf et al. 2011; Ilie et al 2013b]. To date there are few randomized clinical studies that evaluated *in vivo* behavior of these materials: Van Dijken & Pallesen reported comparable Annual Failure Rate between bulk fill composite (class 1: 1.2%; class 2: 2.2%) and conventional composite (class I: 1.0%; class 2: 1.6%) after 3-years of clinical function [Van Dijken & Pallesen 2015].

However several *in vitro* studies focused on bulk fill composites and they confirmed that micro-mechanical properties and degree of conversion are satisfactory in layers of 4 mm polymerized for 20 seconds (Ilie et al 2013a; Zorzin et al. 2015), thus they can be cured in large increments. This is due to several characteristics: the high translucency of these materials, in which the amount of filler decreases but increase its size; the presence of particular photoinitiators and accelerators of the polymerization, more reactive towards curing lights than camphorquinone and leucerin TPO [Ilie & Hickel 2011]. For example, Tetric EvoCeram Bulk Fill contains Ivocerin, a germanium-basedphotoinitiator particularly efficient with a high sensitivity to wavelengths between 400 and 450 nm and which does not require the presence of amine as co-activators [Moszner et al 2008]. Alshali showed that some bulk fill flowable composites, immediately after curing, presented a degree of conversion inferior than traditional composites, but nevertheless they reached a similar degree of conversion after 24 hours. This particular behavior could be advocated to the capacity to reduce shrinkage stress during polymerization [Alshali et al. 2013].

Manufacturers also claim that contraction stress in these new composites is even lower than that found either in flowable either in non-flowable composites [Meereis et al. 2018]. A recent study [Moorty et al 2012] showed that minor contraction stress exerted by bulk fill flowable composites translates into a lower cuspal deflection compared to traditional composites placed with oblique layering technique.

However because of poor mechanical properties [Ilie & Hickel 2011] (hardness and modulus of elasticity are closely related to the amount of filler) [El-Safty et al 2012], the use of low viscosity bulk fill composite is not recommended in situations where high mechanical stress is present, such as in direct contact with occlusal loads. Previous findings [Ilie et al 2013b] showed that Young modulus, Vickers hardness and Indentation modulus classify some bulk fill materials (SureFil SDR, Venus Bulk Fill and Filtek Bulk Bulk) as between hybrid and flowable composites. Moreover, bulk fill composites with increased viscosity were also produced to overcome mechanical limitations and increase clinical indication. Within high viscosity bulk fill composites, Sonic Fill (Kerr) presents a sonic activation through a specific handpiece that allow a transitory viscosity and hardness reduction, which should assure an easier composite adaptation to cavity walls during placement (Alkalin et al. 2018).

The classification of bulk fill materials in low and high viscosity reflects mechanical properties [El-Safty et al 2012, El-Safty et al 2014] and determines clinical procedure: the low viscosity material (SureFil SDR, Venus Bulk Fill, X-tra Base, Filtek Bulk Fill) must be finalized by placing above them a layer of traditional composite, while the high viscosity bulk fill composite (Tetric EvoCeram Bulk Fill, SonicFill) do not need such finalization [Ilie et al 2013b].

If the bulk fill composites are to provide a true clinical advantage, then they require high depth of cure while simultaneously demonstrating a decrease in internal stress, and subsequent decreased incidence of internal gap formation. However, a recent study by Furness [Furness et al. 2014] showed that bulk fill materials, either flowable either non-flowable, resulted in a similar proportion of gap-free marginal interface if compared to a conventional composite.

Composite limitations

Composite restorations longevity was highly variable in literature. Brunthaler *et al.* showed that secondary caries seems to be the most frequent reason for failure of a composite restoration in the period between 6-17 years of functional load [Brunthaler et al. 2003]. Despite the continuing development of composites and subsequent improvement of clinical behaviour [Mjör 1997], optimum mechanical and physical properties of dental composites remain compromised by several factors such as: polymerization shrinkage stress [Davidson et al 1997; Palin et al 2005a; Marchesi et al 2010], limited depth of cure [Jandt et al 2000; Fleming et al 2008], decreased monomer conversion [Palin et al 2003], insufficient wear resistance [Hu et al 2002; Palin et al 2005b], hydrolytic instability [Palin et al 2005c.] and technique sensitivity of application [Lucarotti et al 2005; Opdam et al 2004; Opdam et al 2007]. Thus, the implementation of composite resins mechanical properties and their behavior under mechanical loading is fundamental to increase composite restoration longevity.

References

Aggarwal V, Singla M, Yadav S, Yadav H. Effect of flowable composite liner and glass ionomer liner on class II gingival marginal adaptation of direct composite restorations with different bonding strategies. J Dent. 2014 May;42(5):619-25

Akalın TT, Bozkurt FO, Kusdemir M, Özsoy A, Özcan M. Clinical Evaluation of Sonic-Activated High Viscosity Bulk-Fill Nanohybrid Resin Composite Restorations in Class II Cavities: A Prospective Clinical Study up to 2 Years. Eur J Prosthodont Restor Dent. 2018 Aug 30;26(3):152-160.

Alshali RZ, Silikas N, Satterthwaite JD. Degree of conversion of bulk-fill compared to conventional resin-composites at two time intervals. Dent Mater. 2013 Sep;29(9):e213-7.

Brunthaler A, König F, Lucas T, Sperr W, Schedle A. Longevity of direct resin composite restorations in posterior teeth. Clin Oral Investig. 2003 Jun;7(2):63-70.

Burgess J, Cakir D. Comparative properties of low-shrinkage composite resins. Compendium for Continuing Education in Dentistry. Compend Contin Educ Dent. 2010 May;31 Spec No 2:10-5.

Campos EA, Ardu S, Lefever D, Jassé FF, Bortolotto T, Krejci I. Marginal adaptation of class II cavities restored with bulk-fill composites. J Dent. 2014 May;42(5):575-81.

Chuang SF, Jin YT, Liu JK, Chang CH, Shieh DB. Influence of flowable composite lining thickness on Class II composite restorations. Oper Dent. 2004 May-Jun;29(3):301-8.

Czasch P, Ilie N. In vitro comparison of mechanical properties and degree of cure of bulk fill composites. J Adhes Dent. 2013 Jun;15(3):229-36

Davidson CL, Feilzer AJ. Polymerization shrinkage and polymerization shrinkage stress in polymer-based restoratives. J Dent. 1997 Nov;25(6):435-40.

El-Safty S, Silikas N, Watts DC. Creep deformation of restorative resin-composites intended for bulk-fill placement. Dent Mater 2012 Aug;28(8):928-35.

El-Safty S, Silikas N, Watts DC. Creep deformation of restorative resin-composites intended for bulk-fill placement. J Dent. 2014 Apr;42(4):439-49.

Fleming GJ, Awan M, Cooper PR, Sloan AJ. The potential of a resin-composite to be cured to a 4mm depth. Dent Mater. 2008 Apr;24(4):522-9.

Furness A, Tadros MY, Looney SW, Rueggeberg FA. Effect of bulk/incremental fill on internal gap formation of bulk-fill composites. J Dent. 2014 Apr;42(4):439-49.

Haak R, Wicht MJ, Noack MJ. Marginal and internal adaptation of extended class I restorations lined with flowable composites. J Dent. 2003 May;31(4):231-9.

Hu X, Shortall AC, Marquis PM. Wear of three dental composites under different testing conditions. J Oral Rehabil. 2002 Aug;29(8):756-64.

Ilie N, Hickel R. Investigations on a methacrylate-based flowable composite based on the SDR technology. Dent Mater. 2011 Apr;27(4):348-55

Ilie N, et al. Influence of various irradiation processes on the mechanical properties and polymerisation kinetics of bulk-fill resin based composites. J Dent. 2013a Aug;41(8):695-702.

Ilie N, Bacuta S, Draenert M. Bulk-fill Resin-based Composites: an in vitro assessment of their mechanical performance. Oper Dent. 2013b Nov-Dec;38(6):618-25

Jandt KD, Mills RW, Blackwell GB, Ashworth SH. Depth of cure and compressive strength of dental composites cured with blue light emitting diodes (LEDs). Dent Mater. 2000 Jan;16(1):41-7.

Kwon Y, Ferracane J, Lee IB. Effect of layering methods, composite type, and flowable liner on the polymerization shrinkage stress of light cured composites. Dent Mater. 2012 Jul;28(7):801-9.

Manhart J, Chen H, Hamm G, Hickel R. Buonocore Memorial Lecture. Review of the clinical survival of direct and indirect restorations in posterior teeth of the permanent dentition. Oper Dent. 2004 Sep-Oct;29(5):481-508.

Marchesi G, Breschi L, Antoniolli F, Di Lenarda R, Ferracane J, Cadenaro M. Contraction stress of low-shrinkage composite materials assessed with different testing systems. Dent Mater. 2010 Oct;26(10):947-53.

Meereis CTW, Münchow EA, de Oliveira da Rosa WL, da Silva AF, Piva E. Polymerization shrinkage stress of resin-based dental materials: A systematic review and meta-analyses of composition strategies. J Mech Behav Biomed Mater. 2018 Jun;82:268-281.

Mjör IA. The reasons for replacement and the age of failed restorations in general dental practice. Acta Odontol Scand. 1997 Jan;55(1):58-63.

Moorthy A, Hogg CH, Dowling AH, Grufferty BF, Benetti AR, Fleming GJ. Cuspal deflection and microleakage in premolar teeth restored with bulk-fill flowable resin-based composite base materials. J Dent. 2012 Jun;40(6):500-5.

Moszner N, Fischer UK, Ganster B, Liska R, Rheinberger V. Benzoyl germanium derivatives as novel visible light photoinitiators for dental materials. Dent Mater. 2008 Jul;24(7):901-7.

Oliveira LC, Duarte S Jr, Araujo CA, Abrahão A. Effect of low-elastic modulus liner and base as stress-absorbing layer in composite resin restorations. Dent Mater. 2010 Mar;26(3):e159-69.

Opdam NJ, Loomans BA, Roeters FJ, Bronkhorst EM. Five-year clinical performance of posterior resin composite restorations placed by dental students. J Dent. 2004 Jul;32(5):379-83

Opdam NJ, Bronkhorst EM, Roeters JM, Loomans BA. A retrospective clinical study on longevity of posterior composite and amalgam restorations. Dent Mater. 2007 Jan;23(1):2-8

Lucarotti PS, Holder RL, Burke FJ. Outcome of direct restorations placed within the general dental services in England and Wales (Part 3): variation by dentist factors. J Dent. 2005 Nov;33(10):827-35.

Palin WM, Fleming GJ, Burke FJ, Marquis PM, Randall RC. Monomer conversion versus flexure strength of a novel dental composite. J Dent. 2003 Jul;31(5):341-51.

Palin WM, Fleming GJ, Nathwani H, Burke FJ, Randall RC. In vitro cuspal deflection and microleakage of maxillary premolars restored with novel low-shrink dental composites. Dent Mater. 2005a Apr;21(4):324-35.

Palin WM, Fleming GJ, Burke FJ, Marquis PM, Pintado MR, Randall RC, Douglas WH. The frictional coefficients and associated wear resistance of novel low-shrink resin-based composites. Dent Mater. 2005b Dec;21(12):1111-8

Palin WM, Fleming GJ, Burke FJ, Marquis PM, Randall RC. The influence of short and medium-term water immersion on the hydrolytic stability of novel low-shrink dental composites. Dent Mater. 2005c Sep;21(9):852-63.

Roggendorf M, Krämer N, Appelt A, Naumann M, Frankenberger R. Marginal quality of flowable 4-mm base vs. conventionally layered resin composite. J Dent. 2011 Oct;39(10):643-7.

van Dijken JW. Durability of resin composite restorations in high C-factor cavities: a 12-year follow-up. J Dent. 2010 Jun;38(6):469-74.

van Dijken JW, Pallesen U. Randomized 3-year Clinical Evaluation of Class I and II Posterior Resin Restorations Placed with a Bulk-fill Resin Composite and a One-step Self-etching Adhesive. J Adhes Dent. 2015 Jan 26.

Zorzin J, Maier E, Harre S, Fey T, Belli R, Lohbauer U, Petschelt A, Taschner M. Bulk-fill resin composites: Polymerization properties and extended light curing. Dent Mater. 2015 Mar;31(3):293-301.

1.3 Fiber insertion in composite resins

During masticatory cycle there is a slow and repetitive cycling loading, which decreases the strength of particulate filler composite resins (PFCs). Crack growth can be accelerated by the exposure to water and other fluids that further weaken the resin matrix. However, when stresses are high, the importance of high fracture toughness values becomes significant; at higher stress levels, the materials with higher fracture toughness values perform better [Lassila et al. 2016].

The mechanical properties of PFC can be improved with incorporation of ceramic particle or discontinues fibers [Xu et al 2003, Garoushi et al. 2007]. Fiber reinforced composite is a material combination of polymer matrix, consisting of polymerized monomers, and reinforcing fibers [Garoushi et al 2013]. Fibers can be inserted for injection molding, compressing molding, hydrostatic extrusion and die drawing. [Pinto et al. 2009, Nazhat et al. 2001]

.FRC in dental applications are composed by a matrix of polycarbonate, polyurethane and acryl base polymers, such as poly-methyl-methacrylate (PMMA) and bisphenol-A glycidyl methacrylate (Bis-GMA) reinforced with glass fibers and are generally treated by silane coupling agent to enhance chemical bonds between fiber and polymer matrix. These three factors can influence the mechanical characteristic of FRC [Khan et al. 2015, Van Heumen et al. 2008].

Matrix

PMMM and BisGMA polymer influences the polymerization shrinkage stress (PSS). The selection of the type and the percentage of monomer matrix influence the degree of conversion (DC). Bis GMA has low degree of conversion and give to the resin high viscosity. Co-polymerization of Bis-GMA with UDMA or triethyleneglycol dimethacrylate (TEGDMA) is usually utilized to increase conversion and create highly cross-linked, dense and stiff polymer networks. The elastic modulus has an active role in determining DC rate and PSS development during polymerization.

Moreover, the elastic modulus is enlarged by increase of the filler fraction and BisGMA concentration [Zorzin et al. 2015].

Fiber disposition and distribution:

The orientation of the fibers influence their properties and the fibers can be arranged in three ways:

- Unidirectional: are an isotropic fiber and give at the material the maximal strength when stress is exerted along the direction of the fiber
- Bidirectional: are orthotropic fiber (same properties in two directions with different properties in the third, orthogonal direction)
- Multidirectional: is the typical disposition of the fiber in dental composite.

  These fibers are isotropic: the mechanical properties are the same in all the directions. However, this is accompanied by a decrease in strength in all the direction when compared with unidirectional fiber. These fibers are also a crack stoppers and decreases the polymerization shrinkage [Khan et al. 2015].

Also, the distribution of glass fibers influences FRC properties. If these fibers are equally distributed, the fatigue resistance enhances but if they are located at one place, they can increase the stiffness and strength [Yu et al. 2012].

Resin materials reinforced with short fiber, randomly distributed, obtained higher values of flexural strength, fracture toughness, ad compressive strength [Miettinen et al. 2001].

Meanwhile the position of unidirectional E-glass shows a significant effect on strength and elastic modulusof FRC materials.

Impregnation of fiber

The degree of impregnation of fiber influences the mechanical properties of resin composite. Poor impregnation creates voids between the matrix and the fiber, which decrease the flexural strength and the bond strength and increase the probability of crack growth and propagation along the material.

Void and low degree of impregnation of fiber can also cause water absorption [Lastumäki et al. 2003]. It was reported that water adsorption could decrease mechanical properties of FRC. The water molecules have a radius which is less than 0.158 nm and smaller than the space between the organic chains of the composite material [Mortier et al. 2005]. This causes the water molecules may enter the composite material, particularly in the interface between the filler particles and the polymer network [Olivier & Pharr 1992] [Mortier et al. 2005] determining a hydrolytic degradation and of the empty spaces between the filler particles and the organic matrix. However, the absorption of water is influenced by the degree of polymerization or degree of conversion of the composite, by the type of filler and by the polymer chain. This is because the unreacted phase or dispersed phase inside the material causes voids in which water can penetrate even more easily [Mortier et al. 2005].

Pre-impregnation and silanization, which help to bond the fiber, can decrease water absorption and raise up mechanical properties of these materials. Fibers could be pre-impregnated with polymerized bi-functional acrylate monomers (monomers penetrate in substrate with a free radical polymerization) or inter-diffusion of the monomer (the substrate is a partially non-cross-linked polymer and the penetration of the monomers forms a semi-interpenetrated polymer network) [Khan et al. 2015].

Mechanical properties

The studied mechanical properties of GFRC are flexural strength (FS), flexural modulus (FM), compression strength (CS), diametral tensile strength (DTS), and fracture toughness (FT). [Bijelic-Donova 2016]. Many of these properties are strongly dependent on microstructural parameters such as fiber diameter, fiber length, fiber orientation and fiber loading [Vallittu 2018]. Lassilla suggested that the efficiency of the fiber-reinforcement estimates the strength of FRCs [Lassilla et al. 2016].

His study showed that the mechanical properties of GFRC structure with continuous unidirectional fiber had better results compared to the reinforcement with other fibers, such as short and random. They assigned to unidirectional fiber the value 1 (reinforcing efficiency 100%) which mean that reinforcing properties can be obtained in one direction. Bidirectional (woven, weave) fibers have reinforcing fibers in two directions, therefore, reinforcing the polymer equally in two directions.

However, the woven fibers, add toughness to the polymer, act as crack stoppers and are especially suitable in cases where the direction of the load is unknown or where there is no space for unidirectional fibers. If the fibers were oriented randomly, as in case of a fiber mat or in chopped short FRCs, the mechanical properties were the same in all directions and are so-called isotropic three-dimensionally (MSE). Krenchel showed also that flexural properties of GFRC are higher than the metal post and similar to dentin and they had sufficient and acceptable strength for clinical application under average mastication loads [Lassilla et al. 2016].

Thermal properties

The linear coefficient of thermal expansion (LCTE) depends on the orientation of glass fibers. Continuous unidirectional reinforced fibers have two coefficients of thermal expansion. One lower imposed by the fibers and in the same direction and the second, due to the matrix, that is higher, in the direction perpendicular to the fibers of the polymer matrix. Rigid fibers prevent expansion of the matrix in the longitudinal direction [Khan et al. 2015].

Biocompatibility

Microbial adhesion was observed with glass fibers coated with saliva. The study shows that short glass fiber-reinforced filling material have significantly lower adhesion value compared to dentin and enamel; however, saliva coating significantly decreased the adhesion for FRC materials. Moreover, other study shows that implementation of hydrophobic composite resins with glass fibers reduced the adhesion of microbes on surface [Khan et al. 2015].

References

Bijelic-Donova J, Garoushi S, Vallittu PK, Lassila LV. Mechanical properties, fracture resistance, and fatigue limits of short fiber reinforced dental composite resin. J Prosthet Dent. 2016 Jan;115(1):95-102.

Garoushi S, Vallittu PK, Lassila LV. Short glass fiber reinforced restorative composite resin with semi-inter penetrating polymer network matrix. Dent Mater. 2007 Nov;23(11):1356-62.

Garoushi S, Säilynoja E, Vallittu PK, Lassila L. Physical properties and depth of cure of a new short fiber reinforced composite. Dent Mater. 2013 Aug;29(8):835-41.

Khan AS, Azam MT, Khan M, Mian SA, Ur Rehman I. An update on glass fiber dental restorative composites: a systematic review. Mater Sci Eng C Mater Biol Appl. 2015 Feb;47:26-39.

Lassila L, Garoushi S, Vallittu PK, Säilynoja E. Mechanical properties of fiber reinforced restorative composite with two distinguished fiber length distribution. J Mech Behav Biomed Mater. 2016 Jul;60:331-338.

Lastumäki TM, Lassila LV, Vallittu PK. The semi-interpenetrating polymer network matrix of fiber-reinforced composite and its effect on the surface adhesive properties. J Mater Sci Mater Med. 2003 Sep;14(9):803-9.

Miettinen VM, Vallittu PK, Forss H. Release of fluoride from glass fiber-reinforced composite with multiphase polymer matrix. J Mater Sci Mater Med. 2001 Jun;12(6):503-5.

Mortier E, Gerdolle DA, Dahoun A, Panighi MM. Influence of initial water content on the subsequent water sorption and solubility behavior in restorative polymers. Am J Dent. 2005 Jun;18(3):177-81.

Nazhat SN, Kellomäki M, Törmälä P, Tanner KE, Bonfield W. Dynamic mechanical characterization of biodegradable composites of hydroxyapatite and polylactides. J Biomed Mater Res. 2001;58(4):335-43.

Olivier WC, Pharr GM. An improved technique for determining hardness and elatic modulus using load and displacement sensing indentation experiments. Journal of Materials Research 1992; 7(6) 1564-1583.

Pinto, CED, Arizaga, GGC, Wypych, F, Ramos, LP, Satyanarayana. Studies of the effect of molding pressure and incorporation of sugarcane bagasse fibers on the structure and properties of poly (hydroxy butyrate) composites Part-A. Applied Science and Manufacturing 2009; 40(5) 573-582.

Xu HH, Quinn JB, Smith DT, Giuseppetti AA, Eichmiller FC. Effects of different whiskers on the reinforcement of dental resin composites. Dent Mater. 2003 Jul;19(5):359-67.

Vallittu PK. An overview of development and status of fiber-reinforced composites as dental and medical biomaterials. Acta Biomater Odontol Scand. 2018 Apr 12;4(1):44-55.

Van Heumen CC, Kreulen CM, Bronkhorst EM, Lesaffre E, Creugers NH. Fiber-reinforced dental composites in beam testing. Dent Mater. 2008 Nov;24(11):1435-43.

Yu SH, Lee Y, Oh S, Cho HW, Oda Y, Bae JM. Reinforcing effects of different fibers on denture base resin based on the fiber type, concentration, and combination. Dent Mater J. 2012;31(6):1039-46.

Zorzin J, Maier E, Harre S, Fey T, Belli R, Lohbauer U, Petschelt A, Taschner M. Bulk-fill resin composites: Polymerization properties and extended light curing. Dent Mater. 2015 Mar;31(3):293-301.

1.4 Clinical application of fiber reinforced composite

Fiber can improve the physical characteristics of composite resin. Thanks to their insertion, mechanical and flexural strength of composite acquire higher value. Moreover, they can be used when the loss of dental tissue increases the stress on the restoration and the risk of fracture.

Direct composite restoration

Direct composite restorations are commonly used to restore cavities in both anterior and posterior teeth. The longevity of direct composite restoration is influenced by operator and by the filling material properties. The most common reasons for failure are secondary caries, bulk fractures, marginal deficiencies and wear [Smith & Schuman 1997, Huang et al. 1992, Mondelli et al. 1980]. These aberrations localized on marginal interface are caused by volumetric shrinkage.

Shrinkage of the composite causes stress in the adhesive interface between the restoration and the surrounding tooth tissues. To reduce stress and gap formation and consequently to improve mechanical properties is recommended to use an incremental layering technique while placing a composite restoration. However, this technique is operator-dependent [Joynt et al. 1987, Jagadish & Jogesh 1990]. The insertion of fiber in resin composite can decrease polymerization shrinkage and improved polymerization kinetics than conservative incremental–technique materials [Owen et al. 1986, Gutman et al. 1992, Randow & Glanz 1986]. The filling technique and composite has been shown to have a great impact on the adhesion of restorative composites, in particular in high C-factor cavities [Panitvisai & Messer 1995].

Fiber reinforced composite material adheres well to cavity walls, transferring occlusal loads evenly to the tooth [Schwartz & Robbins 2004, Goerig & Mueninghoff 1983]. Light transmission through fibers is increased such us the polymerization depth. Moreover, its volumetric shrinkage is significantly lower compared to other composite materials [Sorensen & Martinoff 1984] due to the polymerization contraction of SFRC, which is reduced in the direction of the long axis of the fibers [Libermann et al. 1987].

In vitro studies show that the insertion of fiber in restorative composite increases the fracture load of a restoration [Smales & Hawthorne 1997, Cotert et al. 2001] reducing therefore the risk of fracture of extended direct restoration of vital teeth.

Endodontically treated teeth

The endodontically treated tooth is the most subjected to fracture due to the procedure employed during the endo-treatment. The endodontic procedures decrease or alter the tooth structure. This is attributed to caries and previous restorations, fracture or trauma, endodontic access and instrumentation; the weakness is directly correlated to the quantity of removed dentine and it leads to increased cusp deflection during occlusal function. In fact, the prevalence of fracture in vital tooth with large restorations is the same than endodontically treated teeth. The main factor that decreases the resistance of endo-treated tooth is the loss of dental tissue. When tooth lose one or both marginal crests there is a loss of resistance respectively of 46 and 63%, while the only cavity access decrease the resistance only of 5% [Reeh et al 1989]. Moreover, tooth may have a cavity depth 3-4 times greater than a vital tooth, hence the significantly greater risk of fracture. Another factor, which can decrease the resistance of endo-treated teeth, is the modification of dentin. The dentin of endo-treated teeth is substantially different than dentin in teeth with "vital" pulps [Helfer A.R. 1972, Rivera et al 1993]. The dentin in endodontically treated teeth is more brittle because of water loss and loss of collagen cross-linking. However, the dehydration doesn't cause the decrement of the physical or mechanical properties of dentin [Helfer et al. 1972, Papa et al. 1994, Huang et al. 1992, Baba & Goodacre 2014]. Finally, fracture can also start from the root: the endodontic treatment performed with rotary or reciprocating instruments may cause dentinal defects, such as craze lines and cracks, which possibly could develop into fractures after restorative treatment [Baba & Goodacre 2014].

The survival of an endodontically treated teeth depend by the restorative treatment plan.

Teeth can be restored with:

- Full crown
- Adhesive onlay o overlay
- Direct restoration with or without post

It depends by the loss of dental tissue and by the force during the masticatory cycle loading.

Full crown restorations

Full crown is the treatment of election for the endo-treated teeth. Literature support this thesis showing that teeth treated with full crown coverage have an higher term survival rate compared to those not restored with crowns. The teeth restored with crowns have survival rate of 92% at 5 years and 83% at 10 years.

Partial crown restorations

New technologies with the introduction of onlay or overlay adhesive preparation obtain the same result maintaining more sound dental tissue [Sorensen & Martinoff 1984, Linn J, 1994, Cheung GS, 2003]. Comparing with a full crown, partial crown adhesive restoration permits to save more than 50% of dental tissue [Edelhoff & Sorensen, 2002]. Moreover, with partial crown restoration we have better marginal adaptation than crown because the margin is located over the gingival sulcus [Haller e Klaiber, 1989; Shortall, 1989; Milleding, 1992]. These restorations are indicated for extended endodontically second-class restoration when a direct restoration may show an higher risk of fracture.

Post restoration

The purpose of a post is to retain a core in a tooth with extensive loss of coronal tooth structure. The post does not significantly increase the fracture resistance of a restored tooth but is useful in restoration with a large quantity of tissue lost [McComb, 2008].

The success of post restoration depends by the ferrule effect that is the circumferential ring of sound tooth structure that is enveloped by the cervical portion of the crown restoration [Soresen & Engelman, 1990]. A minimum sound dentine height of 1.5-2 mm is required between the core and crown margins [McComb, 2008].

Posts are frequently associated with root fracture. Therefore, posts should be used considering:

- the size and position of the tooth in the arch
- the amount of coronal tooth structure remaining
- the functional requirements of the tooth
- the canal configuration

In anterior teeth post is used only for esthetic and functional reason and for teeth that require rehabilitation with a full crown. In the posterior region, molar teeth rarely require a post unless there has been significant loss of tooth structure; on the contrary posts are generally considered necessary for bicuspid teeth because of their smaller diameter and the presence of high shear stresses, particularly for maxillary teeth [Schwartz & Robbins, 2004].

Post are divided based on their structural and mechanical characteristic in:

- Active and Passive post: the first is intended to engage the walls of the canal, whereas the luting agent retains the second strictly. Active posts are more retentive than passive posts, but introduce more stress into the root providing cracks.
- Conical and cylindrical: conical post requires less dentin removal because most roots are

tapered but they are less retentive than cylindrical post and induce more stress into the root.

- Metallic and not metallic post: metallic post can be custom cast or prefabricated.
  Greater tooth structure is removed for cast posts, and the costs are higher than prefabricated post. Post retention and core retention are similar between the two metallic posts.
  Prefabricated metal posts are available in many different designs and are in stainless steel or titanium [McComb, 2008]. Not metallic posts are composed of various different fiber-reinforced polymer or composite materials, with different designs, sizes and composition.
  Within this group we find carbon fiber post, ceramic post and fiber reinforced composite post.

The insertion of fibers in a not-metallic post is approved to improve his mechanical and physical characteristic. Fibers are incorporated in the matrix resin with the use of a silane and their direction are parallel to the long axis of the post.
Fiber posts have the modulus of elasticity similar to that of dentin [Al-Omiri et al. 2010]; post can be cemented with an adhesive technique avoiding the development of friction between the post and root canal walls [Al-Omiri et al. 2010]. These posts have high fatigue and tensile strength and have a modulus of elasticity comparable with carbon and quartz fiber posts. Moreover, their chemical nature is compatible with the Bis-GMA resins commonly used in bonding procedures (Ferrari et al 2012).

Fiber used to stabilize teeth mobility

The most common use of fiber reinforcement that has been described in the dental literature has been the splinting of teeth. A splint is a device that maintains hard and/or soft tissue in a predetermined position and joins teeth together with the treatment goal of stabilization [Kahler et al. 2016]. Teeth are splinted for a variety of reasons, including to replace missing teeth, to retain teeth that have been orthodontically repositioned, to stabilize teeth that have been traumatized, and to stabilize teeth that are periodontal involved and have mobility. Teeth with mobility are joined with healthy teeth that must be strong enough to support the forces of mastication and the parafunctional forces of grinding, clenching, and trauma. Therefore, to be succesfull, the connectors between the splinted teeth must have a specific thickness to resist fracture in normal function and parafunction; fibers have the characteristic to meet this function [Strassler et al. 2007]. Usually, the splinting is used for the anterior teeth. When anterior teeth are splinted is essential to maintain a long-term durable restoration without compromising esthetic goals. Fibers have good aesthetical characteristic because they are inserted inside a composite matrix. Moreover, pretreatment of fibers permit to have more bond strength value to tooth substrate than metallic splinting.

References

Al-Omiri MK, Mahmoud AA, Rayyan MR, Abu-Hammad O. Fracture resistance of teeth restored with post-retained restorations: an overview. J Endod. 2010 Sep;36(9):1439-49.

Baba N., Goodacre C. Restoration of Endodontically Treated Teeth: Contemporary Concept and Future Prospectives. Endodontic Topics 2014,31,68-83

Cheung W. A review of the management of endodon- tically treated teeth. Post, core and the final restora- tion. *J Am Dent Assoc* 2005: **136**: 611–619.

Cotert HS, Sen BH & Balkan M (2001) In vitro comparison of cuspal fracture resistances of posterior teeth restored with various adhesive restorations The International Journal of Prosthodontics 14(4) 374-378.

Edelhoff D, Sorensen JA. Tooth structure removal associated with various preparation designs for posterior teeth. International Journal of Periodontics and Restorative Dentistry 2002;22:241–9.

Ferrari, M., A. Vichi, and F. Garcia-Godoy, Clinical evaluation of fiberreinforced epoxy resin posts and cast post and cores. Am J Dent, 2000. 13(Spec No): p. 15B-18B.

Goerig AC & Mueninghoff LA (1983) Management of the endodontically-treated tooth. Part II: Technique The Journal of Prosthetic Dentistry 49(4) 491-497.

Gutmann JL (1992) The dentin-root complex: Anatomic and biologic considerations in restoring endodontically-treated teeth The Journal of Prosthetic Dentistry 67(4) 458–467.

Haller B, Klaiber B. Composite inlays as tooth-colored posterior restorations. Zahnarztl Mitt. 1989 Apr 16;79(8):920-5.

Helfer AR, Melnick S, Schilder H. Determination of moisture content of vital and pulpless teeth. Oral Surg Oral Med Oral Pathol 1972;34:661–70.

Huang TJ, Schilder H & Nathanson D (1992) Effects of moisture content and endodontic treatment on some mechanical properties of human dentin Journal of Endodontics 18(5) 209-215.

Jagadish S & Yogesh BG (1990) Fracture resistance of teeth with Class II silver amalgam, posterior composite, and glass cermet restorations Operative Dentistry 15(2) 42-47.

Joynt RB, Wieczkowski G Jr, Klockowski R & Davis EL (1987) Effects of composite restorations on resistance to cuspal fracture in posterior teeth The Journal of Prosthetic Dentistry 57(4) 431-435.

Kahler B, Hu JY, Marriot-Smith CS, Heithersay GS. Splinting of teeth following trauma: a review and a new splinting recommendation. Aust Dent J. 2016 Mar;61 Suppl 1:59-73.

Liberman R, Judes H, Cohen E & Eli I (1987) Restoration of posterior pulpless teeth: Amalgam overlay versus cast gold onlay restoration The Journal of Prosthetic Dentistry 57(5) 540-543.ù

McComb D. Restoration of endodontically Treated Tooth 2008

Milleding P. Microleakage of indirect composite inlays. An in vitro comparison with the direct technique. Acta Odontol Scand. 1992 Oct;50(5):295-301.

Mondelli J, Steagall L, Ishikiriama A, de Lima Navarro MF & Soares FB (1980) Fracture strength of human teeth with cavity preparations The Journal of Prosthetic Dentistry 43(4) 419–422.

Owen CP (1986) Factors influencing the retention and resistance of preparations for cast intracoronal restorations The Journal of Prosthetic Dentistry 55(6) 674-677.

Panitvisai P & Messer HH (1995) Cuspal deflection in molars in relation to endodontic and restorative procedures Journal of Endodontics 21(2) 57–61

Papa J, Cain C, Messer HH. Moisture content of vital vs. endodontically treated teeth. *Endod Dent Traumatol* 1994: **10**: 91–93.

Randow K & Glantz PO (1986) On cantilever loading of vital and non-vital teeth. An experimental clinical study Acta Odontologica Scandinavica 44(5) 271–277.

Rivera EM, Yamauchi M. Site comparisons of dentine collagen crosslinks from extracted human teeth. Arch Oral Biol 1993;38:541–6.

Smales RJ & Hawthorne WS (1997) Long-term survival of extensive amalgams and posterior crowns Journal of Dentistry 25(3-4) 225-227.

Schwartz RS & Robbins JW (2004) Post placement and restoration of endodontically-treated teeth: A literature review Journal of Endodontics 30(5) 289-301.

Smith CT & Schuman N (1997) Restoration of endodonticallytreated teeth: A guide for the restorative dentist Quintessence International 28(7) 457-462.

Shortall AC, Baylis RL, Baylis MA, Grundy JR. Marginal seal comparisons between resin-bonded Class II porcelain inlays, posterior composite restorations, and direct composite resin inlays. Int J Prosthodont. 1989 May-Jun;2(3):217-23.

Sorensen JA, Engelman MJ. Ferrule design and fracture resistance of endodontically treated teeth. *J Prosthet Dent* 1990: **63**: 529–536.

Sorensen JA & Martinoff JT (1984) Intracoronal reinforce- ment and coronal coverage: A study of endodontically-treated teeth *The Journal of Prosthetic Dentistry* **51(6)** 780-784.

Strassler HE, Serio CL. Esthetic considerations when splinting with fiber-reinforced composites. Dent Clin North Am. 2007 Apr;51(2):507-24.

1.5 Aim of the Thesis

Fibers could improve the mechanical characteristic of direct post endodontic restoration. Considering the possible application of FRC, the aim of this study was to:

- Evaluate mechanical properties of FRC;
- Evaluate mechanical properties of FRC, employed in direct composite restoration of endodontically treated teeth;
- Evaluate the fracture pattern of endodontically treated teeth filled with FRC
- Evaluate external and internal marginal GAP of teeth filled with FRC

The specific hypotheses were:

1. Short fiber glass composite has better flexural strength values than commercial composite.
2. The insertion of silanated E- glass fiber can improve flexural strength value.
3. The use of short glass fiber composite in extended direct restoration of endodontically treated teeth can improve mechanical properties and marginal composite adaptations.
4. The insertion of silanated E- glass fiber in can improve mechanical properties and marginal composite adaptations if used in extended direct restoration of endodontically treated teeth.
5. The insertion of fiber in composite resin used for direct extended post endodontic restoration can deflect crack propagation inducing a more favorable fracture.
6. The use of fiber in splinting of traumatized teeth have high survival rate with low complications.

Chapter 2: Material and method & results of the conducted studies

2.1 Research #1: Fracture strength evaluation of composite resins reinforced by different fiber.

Material and Methods

36 rectangular test bar (N=6), were prepared from each tested composite, following ISO standard 4049, of 2 mm x 2mm x 25mm. [Bijelic-Donova J. et al. 2016]

Composite was placed in a single layer of 2 mm in a silicon mold with Plexiglas slide placed on top and cured using a hand light curing unit (Valo, Ultradent) for 40 seconds at 1400 mW/cm^2. After that, to reach a better polymerization, samples were placed in a light-curing oven for 5 minutes (Labolight IV, GC).

Samples were divided in 4 group according with the composite ad the technique employed:

G1: Essentia universal (control Group): it is a micro-hybrid resin composed by: UDMA, dimethacrylate monomers, silicon dioxide, fillers, pigments, photo initiators;

G2: Ever X posterior: it is a short fiber composite resin (SFC). This is a combination of a resin matrix composed by Bis GMA,TEGDMA and PMMA and discontinuous E (electrical) glass fibers, and inorganic particulate fillers.

G3: Admira fusion: a Nano-hybrid Bis-GMA based resin composed of Ba-Al-Si glass particles of $d_{50} = 1$ µm and silica nanoparticles in the range of 10–20 nm in an 84 wt% and a 69 vol% fraction.

G4: Admira Fusion with horizontal fiber (Ever-Stick, GC).

G5: Ever-X posterior with horizontal fiber (Ever-Stick, GC).

For G4 and G5 a single strip of glass fiber network (Ever-Stick.net, GC) were inserted in the middle of the specimen (1mm deep).

Ever-Stick.net is a light-curing bi-dimensional mesh fiber material (thickness of 0.06 mm). It consists in silanated E-glass fibers embedded in an organic polymer matrix of bis-GMA and PMMA.

All prepared samples were stored in a drying oven at 37°C for 24 hours.

Specimens (n = 6) from each group were tested using a three-point flexure test. Tests were conducted at a displacement rate of 1 mm/min and a minimum of six tests were conducted for each set. Loading was continued till the specimen showed catastrophic rupture or the specimen attained a negative slope of load versus displacement with the load drop continuing slowly past peak to below 85% of the peak load.

The maximum breaking loads were recorded in Newton (N) and data were analysed with one-way ANOVA and *post-hoc* Tukey tests ($p<0{,}05$).

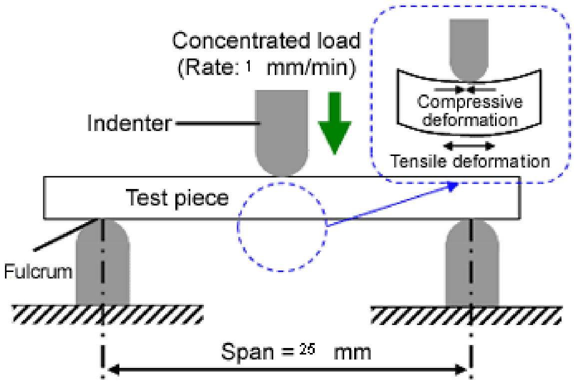


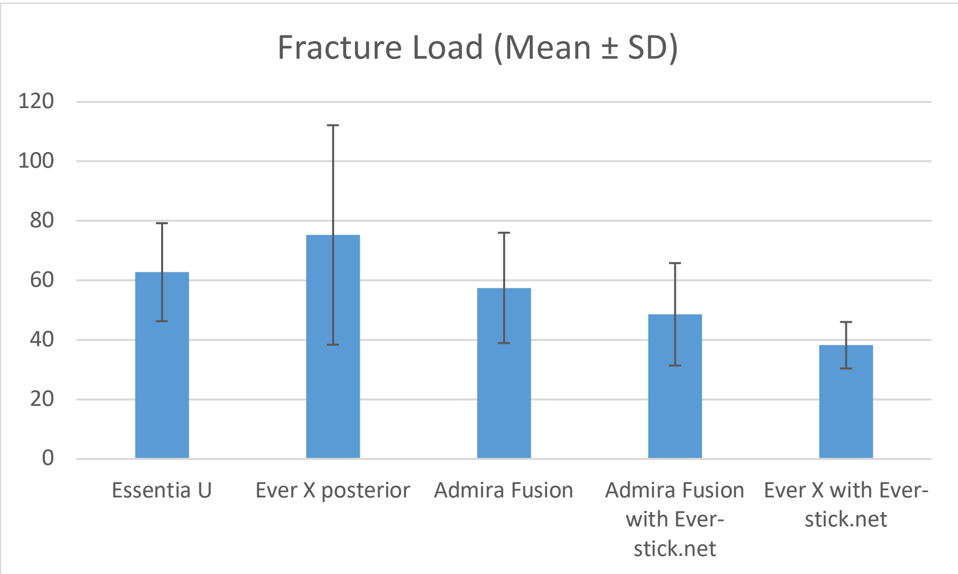
Fig 1. Specimens from each group were tested using a three-point flexure test. Tests were conducted at a displacement rate of 1 mm/min and a minimum of six tests were conducted for each set. Loading was continued till the specimen showed catastrophic rupture or the specimen.

Result:

Mean and standard deviation for static loads in Newton are reported in table 1 and graph 1.

Group	n	Fracture Load (Mean ± SD)
Essentia U	6	62,77 ±16,46[b]
Ever X posterior	6	75,28 ±36,89[a]
Admira Fusion	6	57,50 ±18,54[b]
Admira Fusion with Ever-stick.net	6	48,61 ±17,22[c]
Ever X with Ever-stick.net	6	38,21 ±7,82[d]

Table 1: Mean and sd of tested groups. One-way anova and Bonferroni *post-hoc* test were conducted to determine differences among groups: different lower case letters indicate significant differences within the column $p<0,05$.



Graph 1: mean and standard deviations expressed in Newton for the different tested groups.

Two-way ANOVA test showed that only the variable composite influenced the fracture resistance of the tested groups. The variable fiber insertion did not modify the final values of the tested groups.

The material employed significantly influence flexural strength of the specimen and, in particular, EverX posterior showed the best results of fracture resistance when compared to the other resin tested.

2.2 Research #2: Effects of fiber-glass-reinforced composite restorations on fracture resistance and failure mode of endodontically treated molars.

Materials and methods

Sample selection

In total, 60 non-carious mandibular first molars, extracted forperiodontal reasons, were selected. The inclusion criteria were as follows: sound teeth, with nearly similar crown sizes and no cracks under transillumination and magnification, extracted within 1 month. A hand scaling instrument was used for surface debridement, followed by cleaning with a rubber cup and slurry of pumice.
The specimens were disinfected in 0.5% chloramine for 48 h and then stored in 4% thymol solution at room temperature until use.

Endodontic treatment

Endodontic treatment was carried out in all specimens. Specimens were endodontically instrumented using Pathfiles (1-2-3) and ProTaper Next (Dentsply Maillefer, Ballaigues, Switzerland) to the working length, which was set at 1mm short of the visible apical foramen. Irrigation was with 5% NaOCl (Niclor 5, Ogna, Muggiò, Italy) alternated with 10% EDTA (Tubuliclean,Ogna) using a 2-ml syringe and 25-gauge needle. Specimens were then obturated with gutta-percha (Gutta Percha Points, Medium,Inline; B.M. Dentale Sas Di Bertello G. & Moraes M., Torino, Italy)using the DownPack heat source (Hu- Friedy, Chicago, IL, USA) andendodontic sealer (Pulp Canal Sealer EWT; Kerr, Orange, CA, USA).Backfilling was performed with the Obtura III system (AnalyticTechnologies, Redmond, WA, USA).

Sample preparation

The teeth were stored in distilled water at room temperature for at least 72 h. For the simulation of 0.3-mm-thick periodontal ligament, each root was immersed in melted wax up to the demarcation line 2mm apical to the cement-enamel junction (CEJ; checked with a digital caliper). A metal cubic mold was used to embed all the specimens in acrylic self-curing resin (StickRESIN; Stick Tech Ltd., Turku, Finland) up to 1mm apical to the CEJ, their long axes were oriented perpendicular to the horizon using a custom-made parallelometer. Each root was removed from the resin block when primary signs of polymerization were noticed.
The wax spacer was removed with hot water and then replaced by a silicone-based impression material (Light Body, Flexitime; Heraeus Kulzer, Hanau, Germany), which was injected into the acrylic resin block prior to reinsertion of the specimen.

After 48 h in distilled water, standardized class II mesio-occluso-distal (MOD) cavities were prepared by the same experienced operator in all specimens except the positive control group. For cavity preparation, cylindrical diamond burs (#806314014; Komet, Schaumburg, IL, USA) under copious airwater cooling were used in a high-speed headpiece (Kavo Dental GmbH, Biberach, Germany). The residual thickness of buccal and lingual cusps at the height of the contour was 2.5_0.2mm in all specimens, with the medial and distal cervical margin located 1.5mm coronal to the CEJ (Fig. 2). After finishing the preparation, all internal edges were smoothed and rounded.
according to the post-endodontic restoration.

Group 1 (G1) (positive control): sound teeth (no cavity preparation or root canal treatment).

Group 2 (G2) (negative control): the MOD cavity was not restored.

Group 3 (G3): the MOD cavity was restored with a direct composite restoration. A three-step etch-and-rinse adhesive system (Optibond FL, Kerr) was applied following the manufacturer's instructions, and then cured for 60 s with an LED curing light (Valo; Ultradent Products Inc., South Jordan, UT, USA) at 1400mW/cm2. The cavity floor was covered with a 1mm layer of high viscosity flowable composite (GrandioSo Heavy Flow; Voco,Cuxhaven, Germany), and the cavity was then incrementally restored with composite resin (GrandioSo; Voco) using an oblique layering technique. Each layer, 1.5–2mm thick, was light-cured for 20 s with an LED curing lamp (Valo) at 1400mW/cm2.

Group 4 (G4): the MOD cavity was restored with a fiber post supported direct composite restoration. A post space was prepared to a depth of 7mm, measured from the pulpal chamber floor, using drills from the post manufacturer (Rebilda Post 15; Voco) on the distal canal of the specimen. The root canal walls were cleaned with 10% EDTA for 30 s with a continuous brushing technique, washed using a water syringe with an endodontic needle and then gently air-dried. Excess water was removed from the post space using paper points, preventing the dentin from dehydrating. The post was covered with a layer of silane (Silane Coupling Agent; 3M,St. Paul, MN, USA) and then fixed into the post space with a self adhesive resin cement (Rely-X Unicem 2; 3M). After an initial set for 1 min, irradiation was performed with an LED curing light for 60 s (Valo). Then, a direct composite restoration was performed as described in Group 3.

Group 5 (G5): the MOD cavity was restored with a direct composite restoration reinforced with horizontally placed glass fibers (unidirectional fibers, size 2mm_5mm, 12mm diameter).

After the three-step etch-and-rinse adhesive application described for Group 3, a horizontal layer of high viscosity flowable composite (GrandioSo Heavy Flow) was placed over the pulpal chamber floor until reaching the height of the mesial and distal cervical boxes.

Then, pre-impregnated glass fibers (GranTEC; Voco) were horizontally placed from the mesial to the distal box, without touching the enamel margins. After light-curing for 20 s with an LED lamp (Valo), a direct composite restoration was performed as described in Group 3.

Group 6 (G6): specimens were restored with the same procedure described for Group 5 except with respect to the placement of the glass fibers, which were positioned over the flowable composite in a buccal-palatal direction, with the ends bonded to the buccal and oral walls to achieve a height of 2mm.

All these direct restorations were performed by the same experienced operator, who aimed to obtain an intercuspidal angle of 90° to standardize cusp inclination and allow reproducible positioning of the steel sphere during the compressive tests.

All the restored specimens were finished using a fine diamond bur (8379314016; Komet) and polished with fine Sof-Lex discs (3M)and silicone cups.

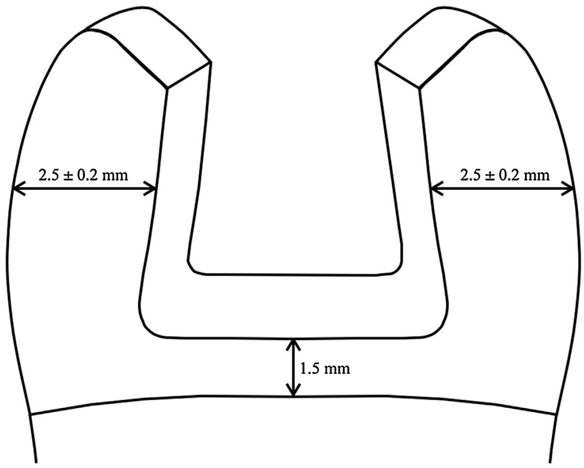


Fig. 2. Schematic representation of the cavity preparation used in this experiment.

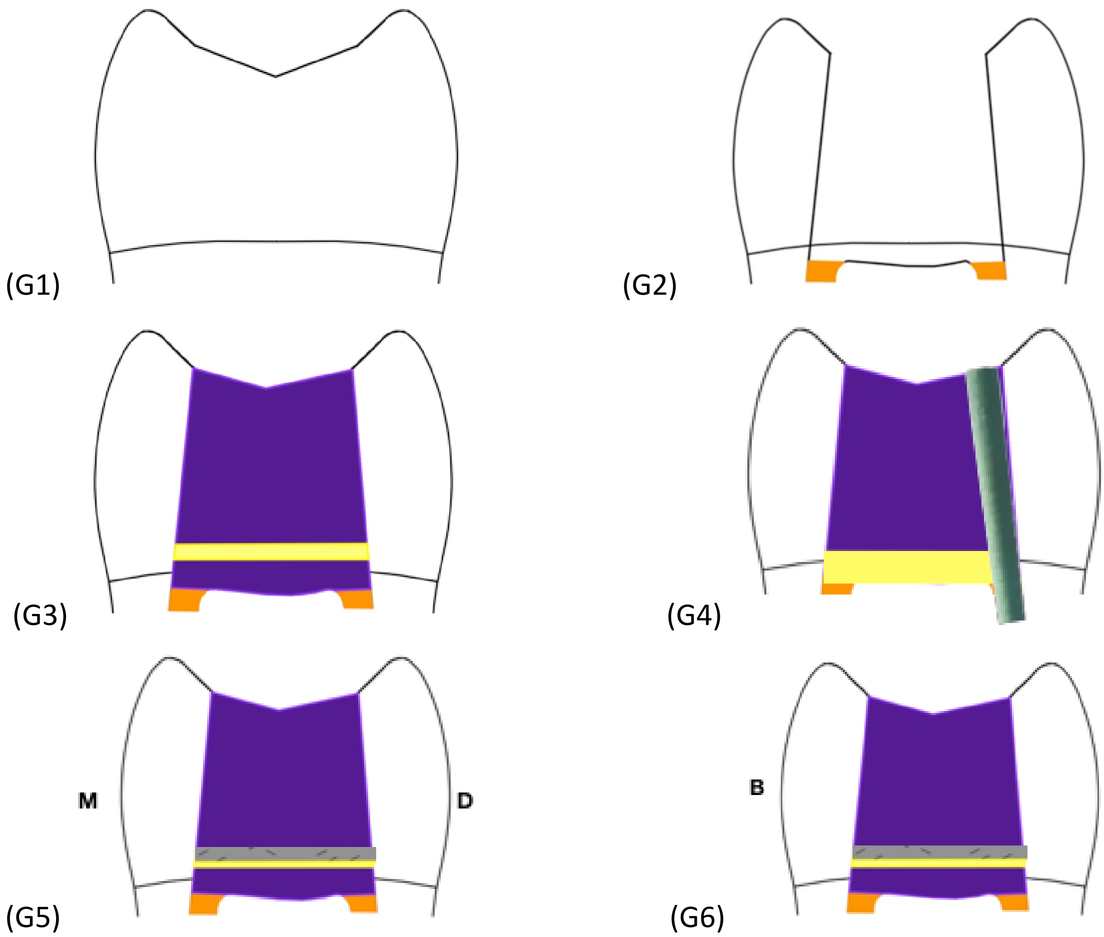


Fig 3*:* Sample preparation: (G1) *Group 1* (sound teeth), (G2) *Group2:*MOD cavity without restoration, (G3) *Group 3:* direct restoration with GrandioSo Heavy Flow and composite resins(Grandioso) (G4) *Group4:* Fiber post restoration with Rebilda post and materials of G3, (G5) Group 5: direct restoration with mesio-distal glass fiber and materials of G3 ,(G6) *Group 6*: direct restoration with bucco-palatal fiber and materials of G3

GrandioSo; Voco

GrandioSo Heavy Flow

GranTEC; Voco

Loading of the specimens

After storage in distilled water at 37°C for 1 week, all specimens were subjected to 5000 thermal cycles between 5°C and 55°C for 60 s and then exposed to 20,000 cycles of 45° oblique loading force on the center of the specimens (Mini Bionics II; MTS Systems, Eden Prairie, MN, USA), at a frequency of 1.3 Hz and 50 N, totally resting on the composite restoration.

Specimens were then submitted to a static fracture resistance test using a universal testing machine (Instron; Canton, MA, USA) with a 6-mm-diameter steel sphere crosshead welded to a tapered shaft and applied to the occlusal surface of the specimens at a constant speed of 0.5 mm/min and an angle of 45°to the long axis of the tooth. Specimens were loaded until fracture and the maximum fracture loads were recorded in Newtons (N).

Fractographic analysis

Fractured specimens were first analyzed under a stereomicroscope (SZX9; Olympus Optical Co., Ltd., Tokyo, Japan). Different magnifications (from 6.3 to 50_) and angled illumination were used to better view the fracture surface. The types of failure were determined and compared; in particular, a distinction was made between catastrophic fractures (non-reparable, below the CEJ) and non-catastrophic fractures (reparable, above the CEJ).

Subsequently a scanning electron microscope (SEM) (Digital SEM XL20; Philips, Amsterdam, Netherlands) was used for more detailed analyses of the fractured surfaces. To clean the specimens of impurities, all fragments were immersed in an ultrasonic 10% NaOCL bath for 3 min, rinsed with water, dried and then fixed on the support for the microscope. The specimens were gold-coated prior to analysis with the SEM. All recognizable features, such as compression curl, hackle, and arrest line [22,23], were photographed and documented. Magnifications up to 2000_ were used to obtain higher definition images of identified crack features in selected areas of interest.

Statistical analysis:

Data are expressed as means standard deviation (SD) and frequency (%). The Kolmogorov-Smirnov test for normality revealed a normal data distribution. The statistical analysis was then conducted with a one-way analysis of variance test (ANOVA) and a post hoc Tukey test. A p-value of <0.05 was considered to indicate statistical significance. All statistical analyses were performed using STATA software (ver. 12.0; Stata Corp, College Station, TX, USA).

Results

The mean values of fracture resistance, expressed in Newtons, obtained in the different groups are listed in Table 2. One-way ANOVA tests revealed significant differences among groups ($p < 0.05$). Further post hoc Tukey tests showed that G1 (sound teeth) had a significantly higher fracture resistance than the other groups, while G2 (non-restored) showed significantly lower values ($p = 0.0001$). The fracture resistance did not differ significantly among G4, G5, and G6, but was significantly higher than that of G3 ($p = 0.001$). In the analysis performed with the stereomicroscope, fractures were evaluated as catastrophic in all specimens, because they were all below the CEJ. In groups where a restoration was performed (i.e., G3–G6), the fractures were always adhesive. The debonding of the restoration occurred on the wall charged with the load; the debonding started from the occlusal surface and determined a deflection of the wall of the tooth that subsequently induced a lateral fracture of the same wall, leaving a "compression curl" marked on the root. Some mixed secondary fractures (adhesive-cohesive) occurred, predominantly in the internal part of the restorations or on the occlusal surface. In G6, the layer of fibers, disposed with a buccal-palatal orientation, induced a partial deflection of the fracture, although they were not able to stop the crack propagation (Fig. 3).

Group		n	Fracture Load (Mean ± SD)	Median	Minimum	Max
G1	Not restored	10	831.83 ±50.94^{a}	849	756.40	879.60
G2	Sound tooth	10	282.86±30.33^{b}	299.3	234.87	314.48
G3	Direct composite restoration	10	364.18 ±48.55 ^{c}	359.86	298.51	448.77
G4	Fiber-post supported composite restoration	10	502.93 ± 43.49 ^{d}	507.23	445.98	567.89
G5	Mesio-distal glass-fiber reinforced composite restoration	10	499.26 ±61.77 ^{d}	487.98	426.65	587.52
G6	Buccal-oral glass-fiber reinforced composite restoration	10	582.22 ±76.50 ^{d}	565.023	499.67	703.31

Table 2. Mean fracture load values, expressed in Newtons, of each group. Different superscript letters indicate statistical differences between groups ($p < 0.05$).

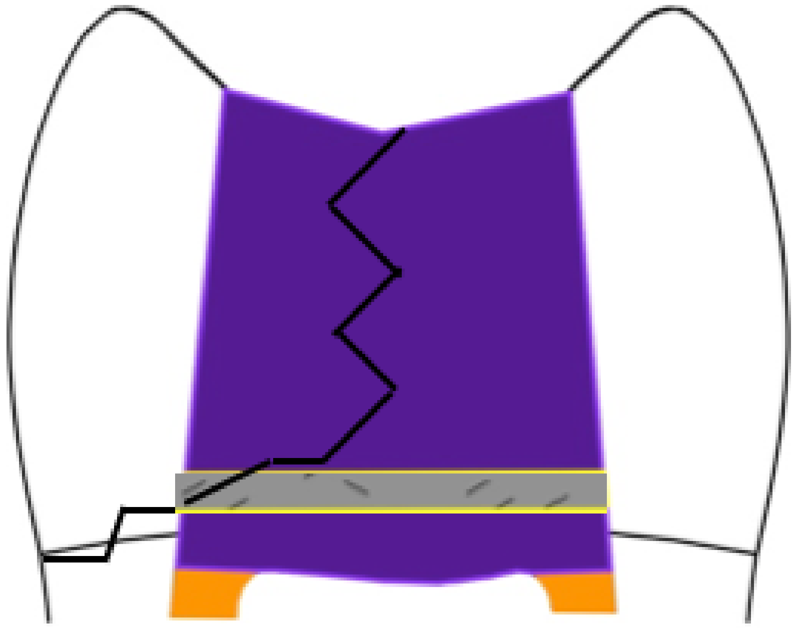


Fig 3. A schema of the partial deviation of the fracture induced by fibers .

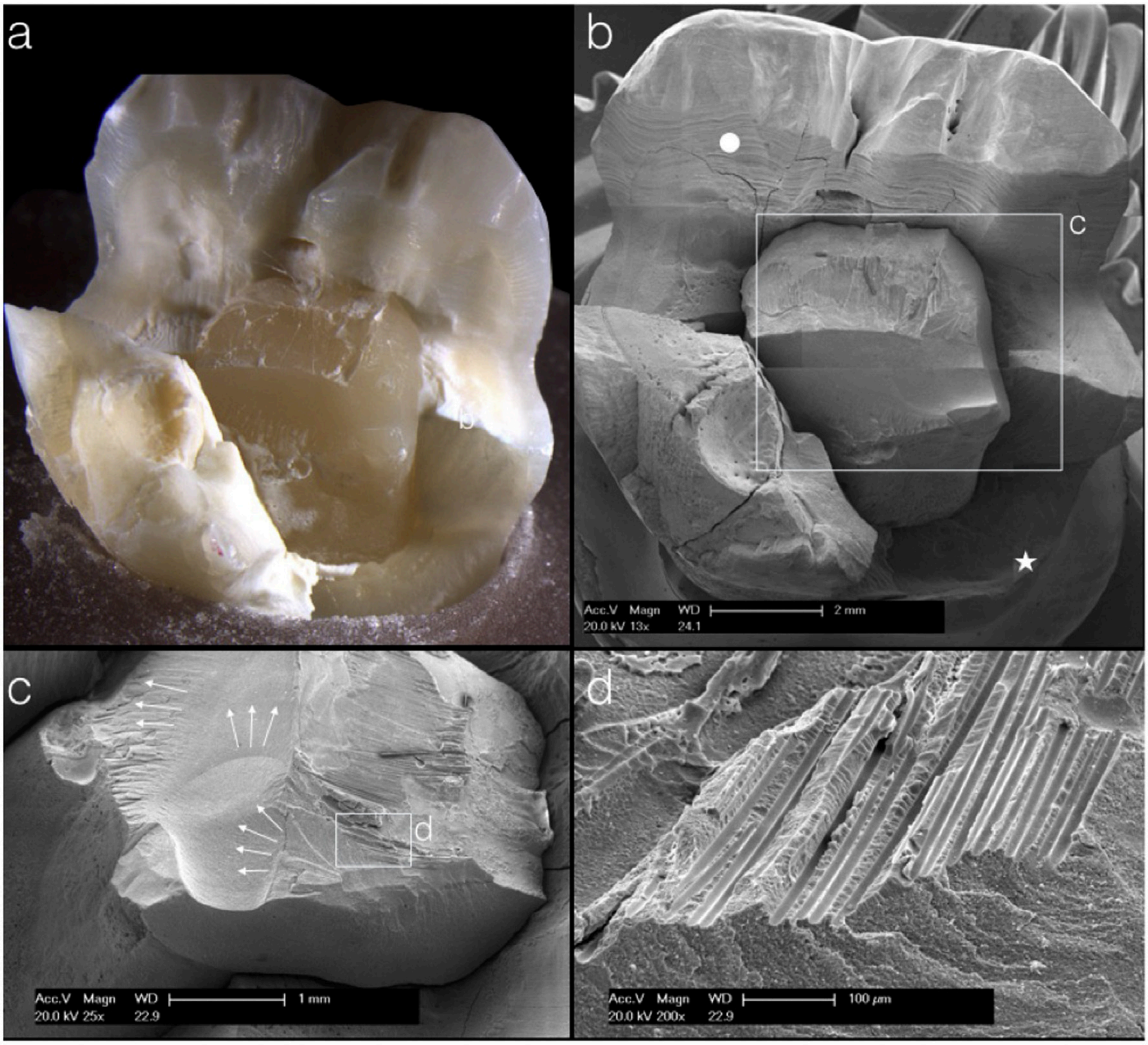


Fig. 4. A fractured specimen from group 6. (a) Stereomicroscope image of the pattern of the fracture. (b) Scanning electron microscope (SEM) image showing the mixed fracture: marks produced by the diamond bur (white circle) were still visible on the internal part of the palatal wall. The fracture ended at the level of the palatal root, where it produced a "compression curl" (white star). The white rectangle c in (b) represents (c). (c) Hackle lines (white arrows) indicate the presence of a partial cohesive fracture of the build-up, and show the direction of the crack propagation. The white rectangle d in (c) represents (d). (d) The layer of glass fiber, which left an impression (white star) on the resin composite build-up, caused a partial interruption of the propagation of the fracture. However, this was not enough to completely stop the crack.

2.3 Research #3: Interfacial gap and fracture resistance of endodontically treated premolars restored with fiber reinforced composites.

Materials and Methods

Sample selection

Eighty-four extracted intact premolars with mature apices, extracted for orthodontic and periodontal reasons, were selected. The inclusion criteria were as follows: sound teeth, with nearly similar crown sizes and no cracks under trans-illumination and magnification, extracted within 1 month. Scaler and hand scaling instrument were used for surface debridement followed by cleaning with a rubber cup and slurry of pumice. Teeth were stored in distilled water at room temperature until required.

Endodontic treatment

Endodontic treatment was carried out in all specimens except for the control group (intact teeth). Samples were endodontically instrumented using Pathfiles (1-2-3) and ProTaper Next X1 and X2 (Dentsply Maillefer, Ballaigues, Switzerland) to the working length, which was set at 1 mm short of the visible apical foramen. Irrigation was with 5% NaOCl (Niclor 5; Ogna, Muggiò, Italy) alternated with 10% EDTA (Tubuliclean, Ogna) using a 2-mL syringe and 25-gauge needle. Specimens were then obturated with gutta-percha (Gutta Percha Points, Medium, Inline; B.M. Dentale Sas Di Bertello G. & Moraes M., Torino, Italy) using the DownPack heat source (Hu-Friedy, Chicago, IL, USA) and endodontic sealer (Pulp Canal Sealer EWT; Kerr, Orange, CA, USA). Backfilling was performed with the Obtura III system (Analytic Technologies, Redmond, WA, USA).

Sample preparation

After 48 hours in distilled water storage, a standardized class II mesio-occluso-distal (MOD) cavity was prepared by the same operator in all specimens except the positive control group. For cavity preparation, cylindrical diamond burs (#806314014; Komet, Schaumburg, IL, USA) under copious air-water cooling were used in a high-speed headpiece (Kavo Dental GmbH, Biberach, Germany). The residual thickness of buccal and palatal cusps at the height of the contour was 2.5 ± 0.2 mm in all specimens, with the medial and distal cervical margin located 1 mm coronal to the CEJ. After finishing the preparation, all internal edges were smoothed and rounded.

In all specimens standardized adhesive procedures were performed. Enamel margins were etched with 36% phosphoric acid (Ultraetch, Ultradent, Ultradent Products Inc., South Jordan, UT, USA) for 40 s, while dentin was etched for 15 s. Specimens were then washed and gently air-dried with an air syringe, preventing the dentin from dehydrating. A multi-mode adhesive (G-Premio Bond, GC, Tokyo, Japan) was applied following manufacturer's instructions and cured for 20 s with a LED curing light (Valo; Ultradent Products Inc.) at 1400 mW/cm^2. Then, specimens were randomly assigned at 7 groups (n=12 each), according to the restorative material employed:

- **Group 1** (G1, positive control): sound teeth (no cavity preparation or root canal treatment);
- **Group 2** (G2, negative control): the MOD cavity was not restored;
- **Group 3** (G3): the MOD cavity was incrementally restored with short fiber reinforced composite (Ever-X Posterior, GC, Japan, EVX), curing each layer 1.5-2 mm thick with an LED curing light (Valo) at 1,400 mW/cm^2 for 20 s, leaving 2mm for placement of top layer using micro-hybrid composite (Essentia U, GC)
- **Group 4** (G4): the MOD cavity was restored with a nano-hybrid resin composite (Filtek Supreme XTE, 3M, USA, FSXTE), which was applied in 2mm layers following an incremental oblique technique. Each layer was light cured for 20 s with an LED curing light (Valo) at 1,400 mW/cm^2 .
- **Group 5** (G5): a horizontal layer of high viscosity flowable composite (Gaenial Flow, GC) was placed over the pulpal chamber floor. Then, glass-fibers (everStick NET, GC) were cut to measure 10mm long and 3mm wide, inserted inside the cavity and adapted over the pulpal floor, in a buccal-oral direction, without reaching the occlusal enamel margins. After light-curing for 20 s with a LED lamp (Valo), a direct composite restoration was performed as described in Group 3.
- **Group 6** (G6): specimens were restored with the same procedure described for Group 5 except for the material used. Direct restoration was performed with FSXTE, which was applied in 2mm layers following an incremental oblique technique. Each layer was light cured for 20 s with an LED curing light (Valo) at 1,400 mW/cm^2.
- **Group 7** (G7): a build-up with nanohybrid composite (Filtek Supreme XTE, 3M) was performed with a 2mm oblique layering technique. Then, a standardized overlay preparation with 2 mm cusp reduction was performed. Composite overlays of 2mm thickness were then prepared on a gypsum cast obtained after monophase bicomponent impression with a light-body putty silicone material (Flexitime; Heraeus Kulzer). Overlays were post-cured (Labolight LV-III; GC, Tokyo, Japan) for 5 min and then cemented using a dual-curing luting system (G-Cem Link Force, GC) following the manufacturer instructions. The overlays were inserted into the cavities and fixed in place manually by applying pressure to the occlusal surface with a large plugger. Excess luting composite was removed with a fine spatula along all sample margins. Polymerization was achieved using a LED curing unit

(Valo) for at least 60 s/surface. The luting composite was cured for an additional 10 s/surface using a thin layer of glycerin gel to eliminate the oxygen-inhibition layer on the surface of the luting composite.

All restorations were realized by the same experienced operator, who aimed to obtain an intercuspidal angle of 90° to standardize cusp inclination and allow reproducible positioning of the steel sphere during the compressive tests. All restored specimens were finished using a fine diamond bur (8379314016; Komet) and polished with fine Sof-Lex discs (3M) and silicone cups and then stored in distilled water at 37°C for 1 week. Sample preparation is showed in *Figure 4*

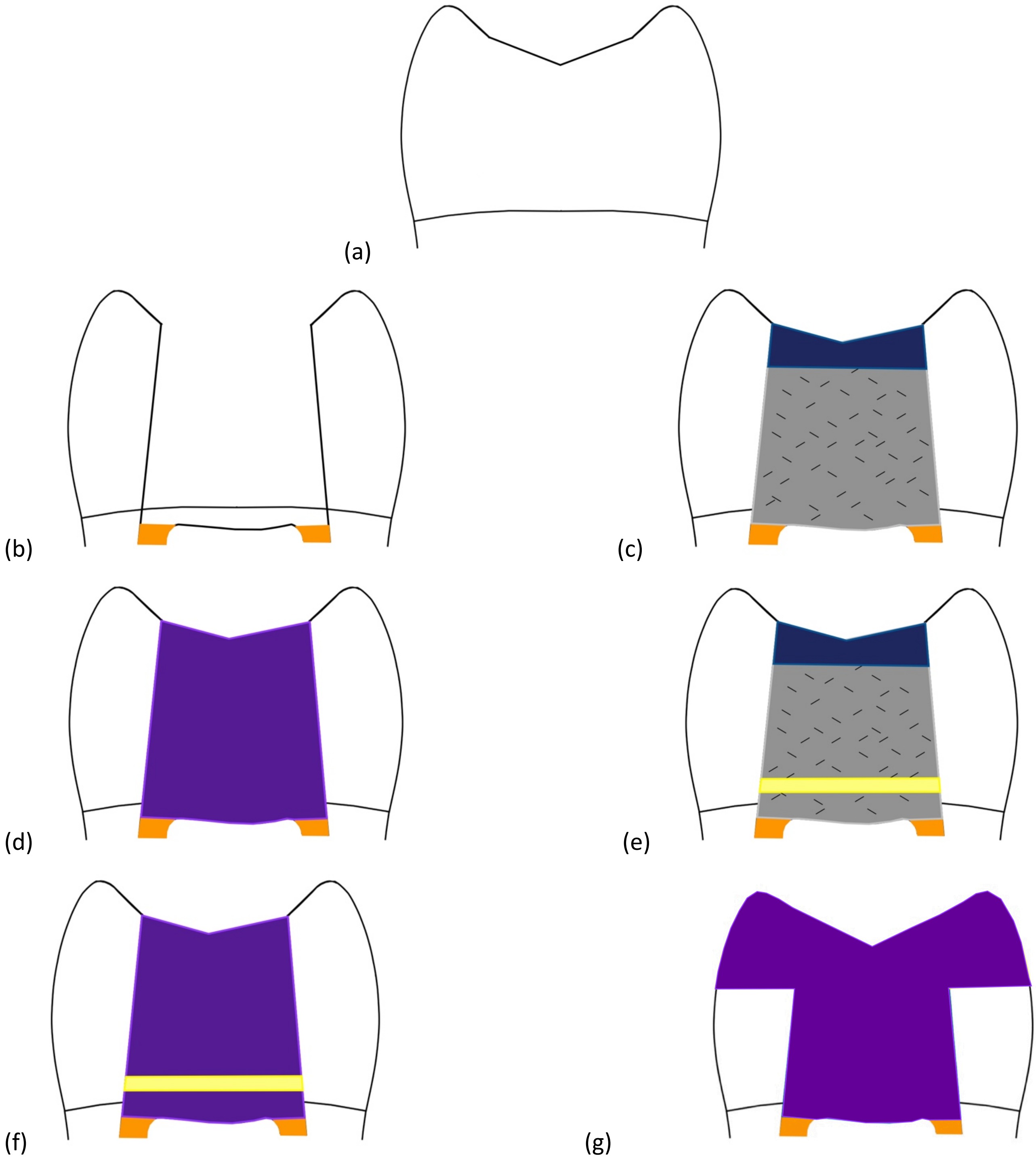


Figure 4*:* Sample preparation: (a) *Group 1* (sound teeth), (b) *Group2:*MOD cavity without restoration, (c) *Group 3:* direct restoration with Ever X, (d) *Group4:* direct restoration with Filtek Supreme XTE, (e) Group 5: direct restoration with Ever X ad fiber (everStick NET) in the bottom of the cavity, (f) *Group 6*: direct restopration with Filtek Supreme XTE and fiber (EverStick.NET) on the bottom of the cavity, (g) *Group 7*: overlay on Filtek Supreme XTE build-up

essentiaU
Filtek Supreme
EverX Posterior
Gaenial Flow

Micro- CT analysis and fatigue artificial treatment

The marginal integrity of each restoration was evaluated using a Micro-CT scan (SkyScan 1172 Micro-CT, Bruker). Specimens were scanned setting parameters for the high-resolution scans: voltage = 100 kV, current = 100 µA, source to object distance = 80 mm, source to detector distance = 220 mm, pixel binning = 292, exposure time/projection = 3s (total scan duration = 2 h), aluminum and copper (Al+Cu) filter. N Recon software and Data Viewer software were used to reconstruct specimens and to obtain 3D images.

Specimens were stored in distilled water at 37°C for 24 h and then cleaned for 10 min by sonication. A CS-4.4 chewing simulator (SD Mechatronik; Feldkirchen- Westerham, Germany) was used for fatigue cycling mechanical aging of the specimens. A 0.25-0.5mm-thick layer of light of silicon impression material (Express,3M ESPE) was added surrounding the roots specimens over the CEJ, in order to simulate periodontal ligaments. A 6-mm- diameter steatite sphere was applied using an occlusal load of 30 N, a frequency of 1 Hz, and a downward speed of 16 mm/s. The sphere is positioned on tooth to obtain a loading force on the mesio-buccal, disto-buccal, and palatal cusps (tripod contacts). The test was performed for 72 h, which corresponded to 250000 cycles

To reveal the interfacial marginal gap progression between the restoration and the tooth structure after cycling fatigue, specimens were subjected to a second scan with same parameters of the baseline to ensure consistency in the greyscale values. Initial scans were then aligned with post-chewing scans using DataViewer TM software (Bruker microCT), and then reconstructed with NRecon using the same protocol. Thresholding was performed automatically with Mimics Medical 20.0 software (Materialise), in order to obtain a void mask representing the voids between the restoration and the tooth. Using dynamic region growing function, only external gap was considered in the present study. Representative samples were also chosen for 3D reconstruction using the SkyScan CT-Vox program (Bruker microCT)

Fracture resistance test

Specimens were then submitted to a static fracture resistance test using a universal testing machine (Instron; Canton, MA, USA) with a 6-mm-diameter steel sphere crosshead welded to a tapered shaft and applied to the specimens at a constant speed of 0.5 mm/min and an angle of 45° to the long axis of the tooth. Load was applied perpendicular to the palatal cusp[18]. Samples were loaded until fracture and the maximum breaking loads were recorded in Newton (N).

Failure mode analysis

Broken specimens were first analyzed under a stereomicroscope (SZX9; Olympus Optical Co., Ltd., Tokyo, Japan). Different magnifications (from 6.3 to 50×) and angled illumination were used to better view the fracture surface. The types of failure were determined and compared; in particular, a distinction was made between catastrophic fractures (non-reparable, below the CEJ) and non-catastrophic fractures (reparable, above the CEJ).

Statistical analysis

Data are expressed as means ± standard deviation (SD) and frequency (%). The Kolmogorov-Smirnov test for normality revealed a normal data distribution. The statistical analysis was conducted with a two-way ANOVA to examine the effects of the factors “fibers” and “restoration” (Filtek vs Ever-X vs Overlay) and their interactions on the fracture resistance and the interfacial marginal gap progression. Post-hoc pairwise comparisons were performed using the Tukey test. The chi-square test was used to analyze differences in the failure modes. For all statistical analyses, statistical significance was pre-set at $p<0.05$. All statistical analyses were performed by using Stata 12.0 (StataCorp, College Station, Texas, USA).

Result

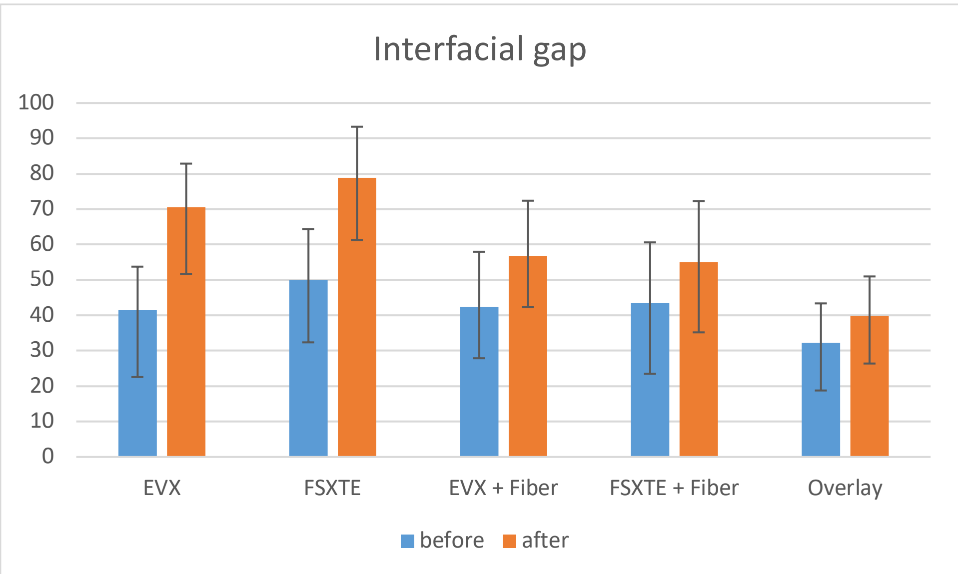
Means (±SD) of interfacial gaps, expressed in µm^3, before and after fatigue load, obtained in different groups are displayed in Table 1. Regarding the interfacial marginal gap analysis, two-way ANOVA showed a significant increase in marginal gaps after chewing simulation only in Group 3 ($p=0.0001$) and in Group 4 ($p=0.0001$). Thus, the insertion of horizontal glass fibers reduced the interfacial gap propagation after fatigue loading as well as the use of composite overlay.

Fracture resistance, expressed in Newton, obtained in different groups are listed in Table 3. Two-way ANOVA showed a significant difference for the variable "restoration" ($p=0.00001$, $f=75.59$) but not for the variable "fiber insertion" ($p=0.0628$, $f=9.96$), neither for the interaction between restoration and fiber insertion ($p=0.83$, $f=0.04$). Post-hoc Tukey test showed that sound teeth had a significantly higher fracture resistance than other groups, while non-restored cavities presented significantly lower values. No differences in fracture resistance were found between Filtek Supreme and Ever-X, while the fiber insertion improved the fracture resistance of both composites even if not significantly. In addition, the composite overlay achieved significantly better fracture resistance than the direct restoration techniques tested, regardless of the material used.

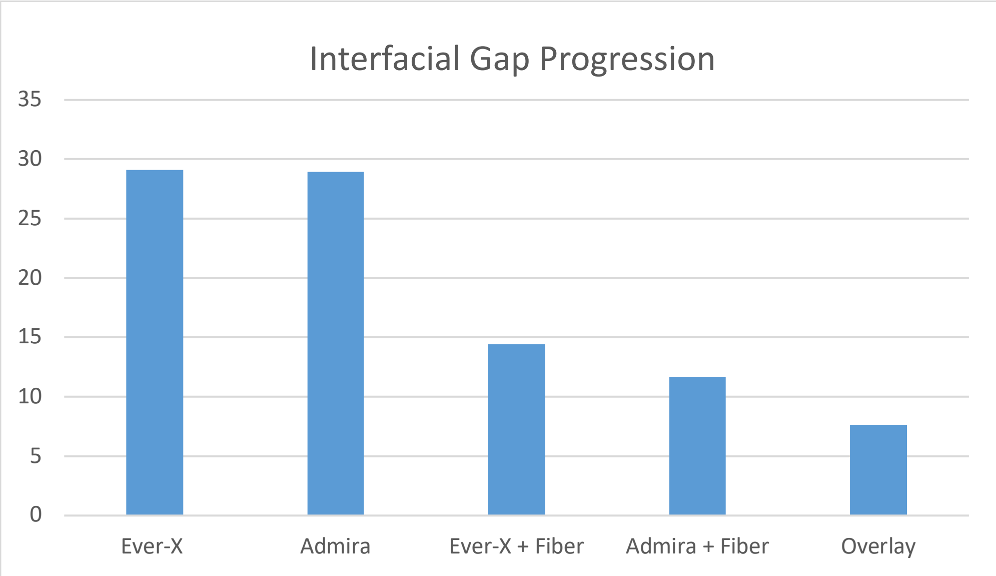
Stereomicroscope analysis revealed catastrophic fractures (below the CEJ) in all specimens.

	G3(Ever-X Posterior)	G4(Filtek Supreme XTE)	G5(Ever-X Posterior+Fiber)	G6(Filtek Supreme XTE + Fiber)	G7(Composite Overlay)
Before	41.473 (±12.311)	49.873 (±14.508)	42.383 (±15.637)	43.423 (±17.207)	32.182 (±11.256)
After	70.575 (±18.925)	78.822 (±17.521)	56.811 (±14.562)	55.102 (±19.901)	39.812 (±9.826)

Table 3: Mean interfacial gap, expressed as µm^3, before and after chewing simulation obtained in different groups.



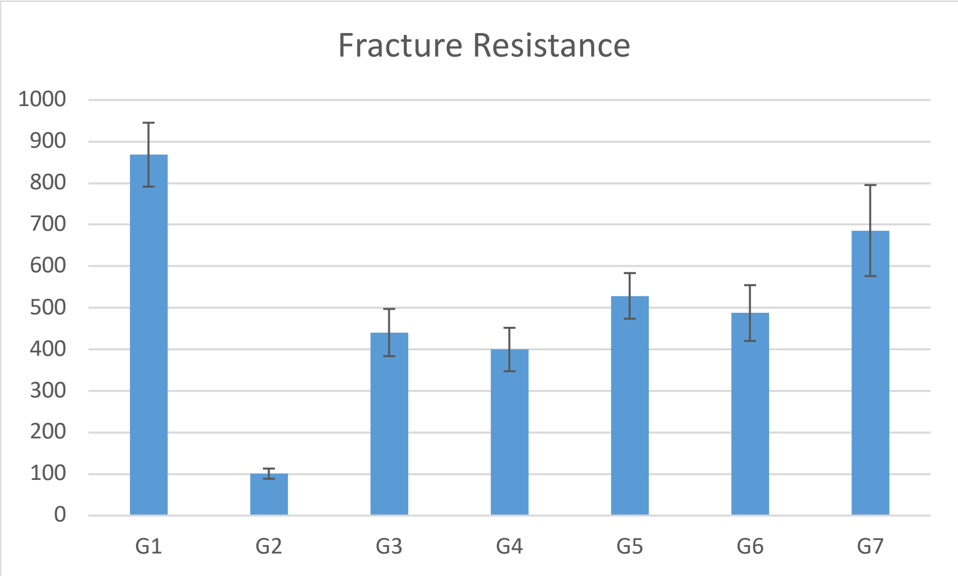
Graph 3: Mean interfacial gap progression, expressed as mm^3 of volume increase after fatigue load, obtained in different groups.



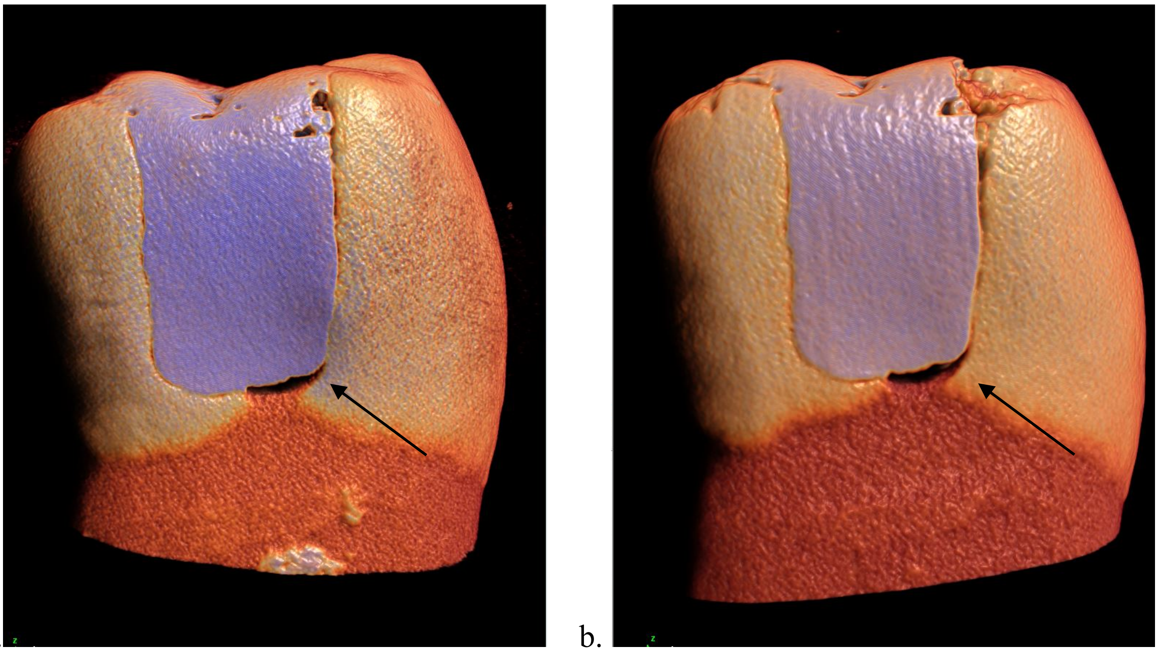
Graph 4: Marginal gap progression obtained in different groups.

Group	**n**	**Fracture Load (Mean ± SD)**	**Minimum**	**Max**
1(Sound tooth)	12	934.91 ±143.08 [a]	569.66	1039.45
2(Unrestored Cavity)	12	100.80±12.28 [d]	86.51	120.10
3(Ever-X Posterior)	12	415.36 ±66.71 [b]	376.01	630.01
4(Filtek Supreme)	12	411.92 ± 60.39[b]	383.70	587.24
5(Ever-X Posterior with glass-fibers)	12	515.96±72.54 [b]	480.79	773.19
6(Filtek Supreme with glass-fibers)	12	499.79±66.77 [b]	307.77	699.43
7(Composite overlay)	12	705.70±123.62 [c]	519.86	939.46

Table 4: Mean fracture load, expressed in Newton, obtained in different groups. Differences were considered significant at $p<0.05$. Groups with the same superscript letters were not statistically significant ($p>0.05$).



Graph 5: Mean fracture resistance, expressed in N, obtained in different groups.



a. b.

Fig 5: Figure representing the 3D renderings of group EverX+fibers (a) before cycling load (b) after cycling load. Arrows indicate the presence of gap progression.

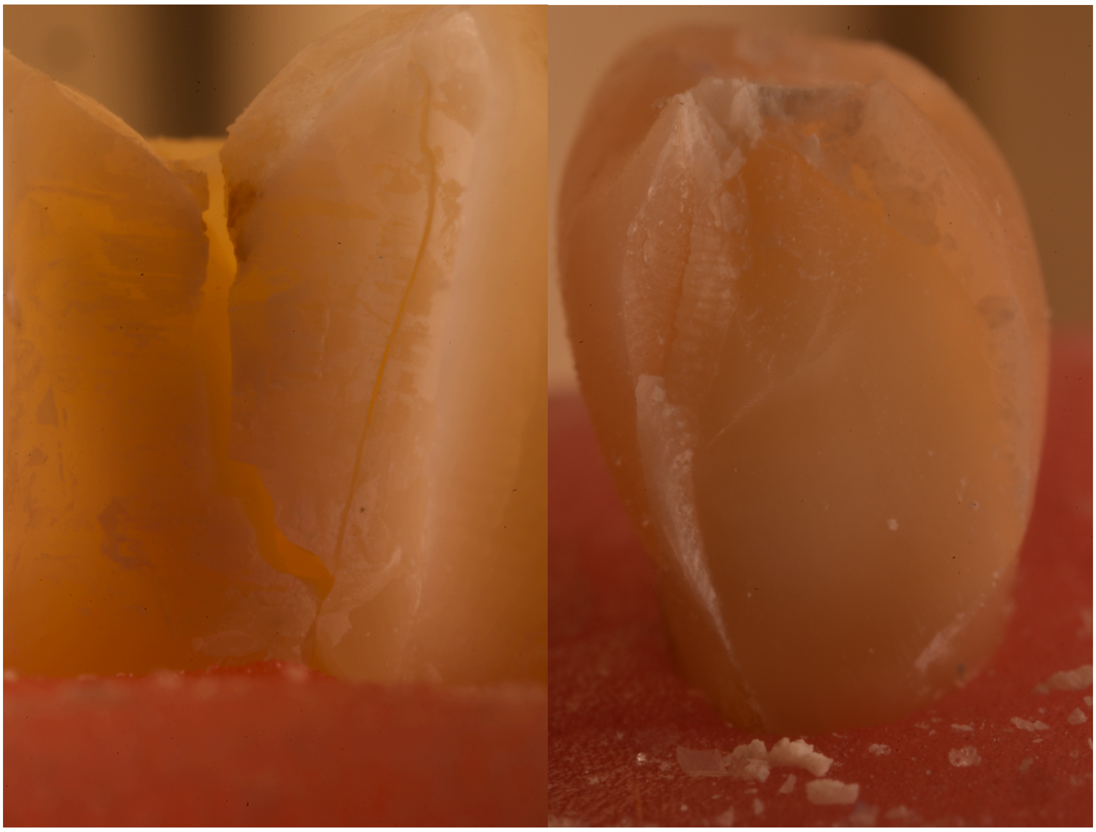


Fig 6: These two images shows examples of catastrophic fractures, which run below the CEJ.

2.4 Research #4: Fracture strength of fiber reinforced composite direct restoration in extended MOD cavities of endodontically treated molars.

Materials and Methods

Samples selection

40 lower intact molars, extracted for periodontal reasons, were selected. The inclusion criteria were: nearly similar crown and root sizes, and no cracks under transillumination. A hand scaling instrument was used for surface debridement of the teeth, followed by cleaning with a rubber cup and slurry of pumice.

Endodontic treatment

Endodontic treatment was carried out in all specimens. Samples were endodontically instrumented using Pathfiles (1-2-3) and ProTaper Next (Dentsply Maillefer, Ballaigues, Switzerland) to the working length, which was set at 1 mm short of the visible apical foramen. Irrigation was with 5% NaOCl (Niclor 5; Ogna, Muggiò, Italy) alternated with 10% EDTA (Tubuliclean, Ogna) using a 2-mL syringe and 25-gauge needle. Specimens were then obturated with gutta-percha (Gutta Percha Points, Medium, Inline; B.M. Dentale Sas Di Bertello G. & Moraes M., Torino, Italy) using the DownPack heat source (Hu-Friedy, Chicago, IL, USA) and endodontic sealer (Pulp Canal Sealer EWT; Kerr, Orange, CA, USA). Backfilling was performed with the Obtura III system (Analytic Technologies, Redmond, WA, USA).

Samples preparation

After endodontic treatment, a mesio-occluso-distal cavity was prepared from a single operator with standardized dimensions: Cervical margin 1 mm above the CEJ; residual wall cavity comprised between 1.5 and 2 mm. Then, samples were divided in 4 groups (n=10 each) according to the restoration technique: Group A: CAD-CAM adhesive overlay with nano-ceramic material; Group B: direct restoration with short fiber-reinforced composite; Group C: direct restoration with nanohybrid composite; Group D: direct restoration with nanohybrid composite with glass fiber reinforcement.

In all samples, the adhesive system (G-Premio Universal Bond, GC) was applied is an etch&rinse mode (37% phosphoric acid for 40 sec in enamel, 15 sec in dentin) and light-cured for 40 sec with a LED curing light (D-Light Pro, GC). Then, a 0.5mm layer of flowable composite is applied to seal the dentin and light cured for 20 sec. Finally, the cavity is incrementally restored, based on the group, and each 1.5-2 mm thick layer is cured for 20 seconds.

- *Group A*: build-up is performed with Essentia U (GC). Then, 1.5mm cusp reduction was performed and external margins were beveled. After optical scan (Omnicam, Sirona), an overlay was designed with Cerec 4.5.2 software and then milled in extra-fine mode. A CAD/CAM nanoceramic block (Cerasmart, shade A2 LT) was employed. After finishing and polishing with a fine diamond bur (8379314016; Komet) and fine Sof-Lex discs (3M) and silicone cups, the overlays was luted with a universal adhesive (G-Premio bond) and Essentia U shade as cement, which was pre-heated at 54°C for 10 minutes. After overlay adaptation and composite excess removal with brushes, light curing was performed for 60sec per side with a LED lamp (VALO, Ultradent) at 1400mW/cm^2.
- *Group B*: after circumferential matrix application, interproximal walls were created with nanohybrid composite (Essentia U-shade, GC). Then, a short fiber-reinforced composite (Ever-X Posterior, GC) was layered until 1mm below the occlusal surface, which was completed with nanohybrid composite. Each composite layer was light cured for 20 sec with a LED lamp (VALO, Ultradent) at 1400mW/cm^2.
- *Group C:* after circumferential matrix application, a nanohybrid composite (Essentia U-shade, GC) was employed to restore the samples following the centripetal build-up technique. Each composite layer was light cured for 20 sec with a LED lamp (VALO, Ultradent) at 1400mW/cm^2.
- *Group D:* in each sample, a single layer of bidirectional E-glass fiber(EverStick.net) were inserted. After circumferential matrix application, interproximal walls were created with nanohybrid composite (Essentia U-shade, GC). Then, after a 2mm layer of Essentia, glass fibers (Everstick.net, GC) were adapted with a buccal-oral direction and compressed with a transparent silicon key before light curing. Finally, a 2 mm layer of nanohybrid composite was applied to complete the direct restoration. Every composite resin layers were cured for 20 sec with a led lamp (VALO, Ultradent) at 1400mW/cm^2.

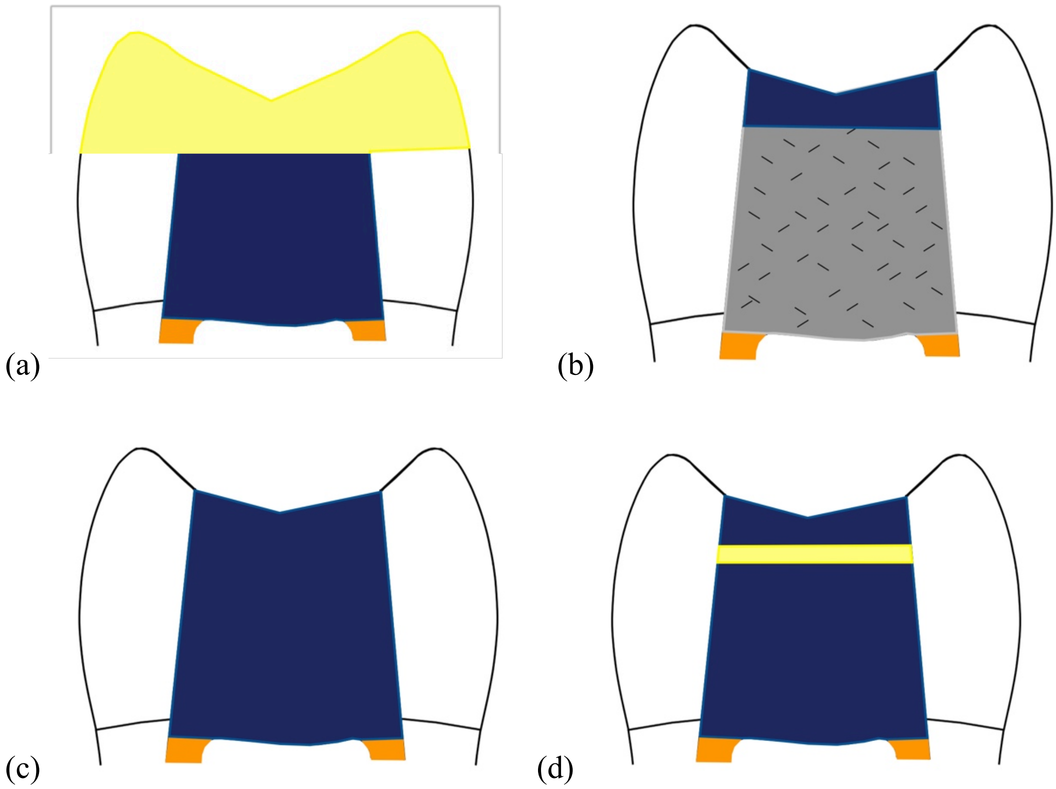


Figure 6: Sample preparation. (a) *Group A*: build-up is performed with Essentia U (GC). An overlay is milled from a CAD/ CAM composite resin block (Cerasmart, shade A2 LT) over a build up. (b) Interproximal walls are created with Essentia U shade. Then, Ever-X posterior is layered until 1mm below the occlusal surface, which was done with Essentia U shade. (c) Essentia U shade was employed to restore the samples following the centripetal build-up technique. (d) EverStick.net glass fiber are inserted on the restoration. Sample are restored as described in group C and the Fibers are adapted in the occlusal side of the restoration with a silicon key and cured for 20sec.Than fibers are covered with a final occlusal layer,

Cerasmart overlay

Essentia U

EverX Posterior

Fracture strength test

All the restored specimens were finished, polished, and then stored in distilled water at 37°C for 7 days. The specimens were then submitted to the static fracture resistance test using a universal testing machine (Instron, Canton, MA, USA) with a 2-mm diameter steel sphere crosshead welded to a tapered shaft and applied to the specimens at a constant speed of 2 mm/min and at an angle of 30° to the long axis of the tooth. Fractured specimens were assessed for failure modes: "restorable failures" including adhesive failures above the CEJ, and "non- restorable failures" including vertical root fractures below the CEJ. Maximum fracture loads were recorded in Newton.

Fractography analysis:

After fracture all the specimens were visually examined in order to establish which fragments were suitable for fractographic analysis. Broken specimens were first analyzed under a stereomicroscope (SZX9; Olympus Optical Co., Ltd., Tokyo, Japan). Different magnifications (from 6.3 to 50×) and angled illumination were used to better view the fracture surface. All detectable fracture surface features were photographed. Scanning Electron Microscopy (SEM) (Digital SEM XL20, Philips) was then used to capture more details of the fractured surfaces. Before SEM analysis, all fragments were pass in an ultrasonic 10% sodium hypochlorite bath for 3 min, rinsed with water and dried. Subsequently they were then gold coated and analyzed with MEB under magnifications up to 2000x in order to obtain high definition of the specific crack features in the selected areas of interest. Fracture patterns of all broken specimens were visually analyzed and considered in two typical configurations: catastrophic fractures (non-reparable, below the CEJ) and non-catastrophic fractures (reparable, above the CEJ). Classification was based on an agreement between three examiners.

Statistical analysis

Data are expressed as means ± standard deviation (SD) and frequency (%). The Kolmogorov-Smirnov test for normality revealed a normal data distribution. The statistical analysis was then conducted with a one-way analysis of variance test (ANOVA) and a post hoc Tukey test. A p-value of < 0.05 was considered to indicate statistical significance. All statistical analyses were performed using STATA software (ver. 12.0; StataCorp, College Station, TX, USA).

Results

Mean values and standard deviation of static loads expressed in Newton are shown in table 5 and graph 6.

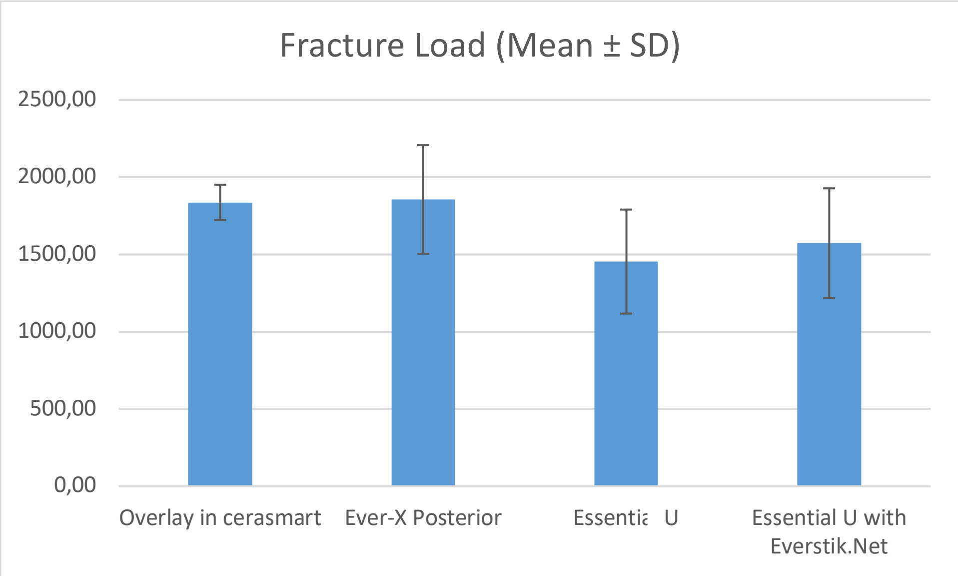
Two-way ANOVA test showed statistically significant difference among different groups. Group 1 and group 2 presented the highest values of strength when compared to the other groups. However there were no difference between this two groups. The variable "fiber insertion" did not significantly altered the fracture resistance of the tested groups.

Modes of fracture were classified as shown in Table 4. In the visual analysis fractures were evaluated as catastrophic (Split), which propagated through different layers of restoration into the tooth cavity under the CEJ, and reparable, which propagated laterally and ended over the CEJ.

Analysis performed with stereomicroscope and SEM highlighted different fracture features (Fig. 1 and 2). Origins of the fractures were always located on the occlusal surface, mainly from the major contact loading area of the loading ball. The direction of the crack was indicated by hackles and always propagates corono-apically. The crack origin corresponded always with the major contact area underneath the horizontal loading indenter. Multiple secondary events were often detected elsewhere at the occlusal surface corresponding to minor loading areas (Fig. 9).

Group	**n**	**Fracture Load (Mean ± SD)**	**Min Load**	**Max Load**
A(Cerasmart overlay)	10	1837,13±113.688 ^{a}	1693,828	2000.101
B(Ever-X Posterior)	10	1855.862±351,314^{a}	905,162	2000,113
C (Essentia U)	10	1454,219±336,546^{c}	733,039	1916,235
D(EssentiaU+Everstik-Net)	10	1572,585±355,559^{b}	912,848	2000,114

Table 5. Mean fracture load, expressed in Newton, obtained in different groups. Differences were considered significant at $p<0.05$. Groups with the same superscript letters were not statistically significant ($p>0.05$).



Graph 6: mean and standard deviations expressed in Newton for the different tested groups.

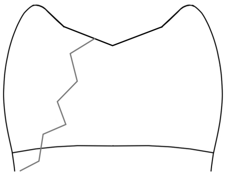
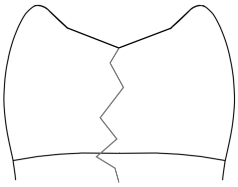
	GROUP A	GROUP B	GROUP C	GROUP D
REPARABLE 	1	6	3	1
NON-REPARABLE 	9	4	7	9

Fig. 7. Fracture patterns for the different tested groups (Reparable fracture over the CEJ and non-reparable fracture under the CEJ or SPLIT).

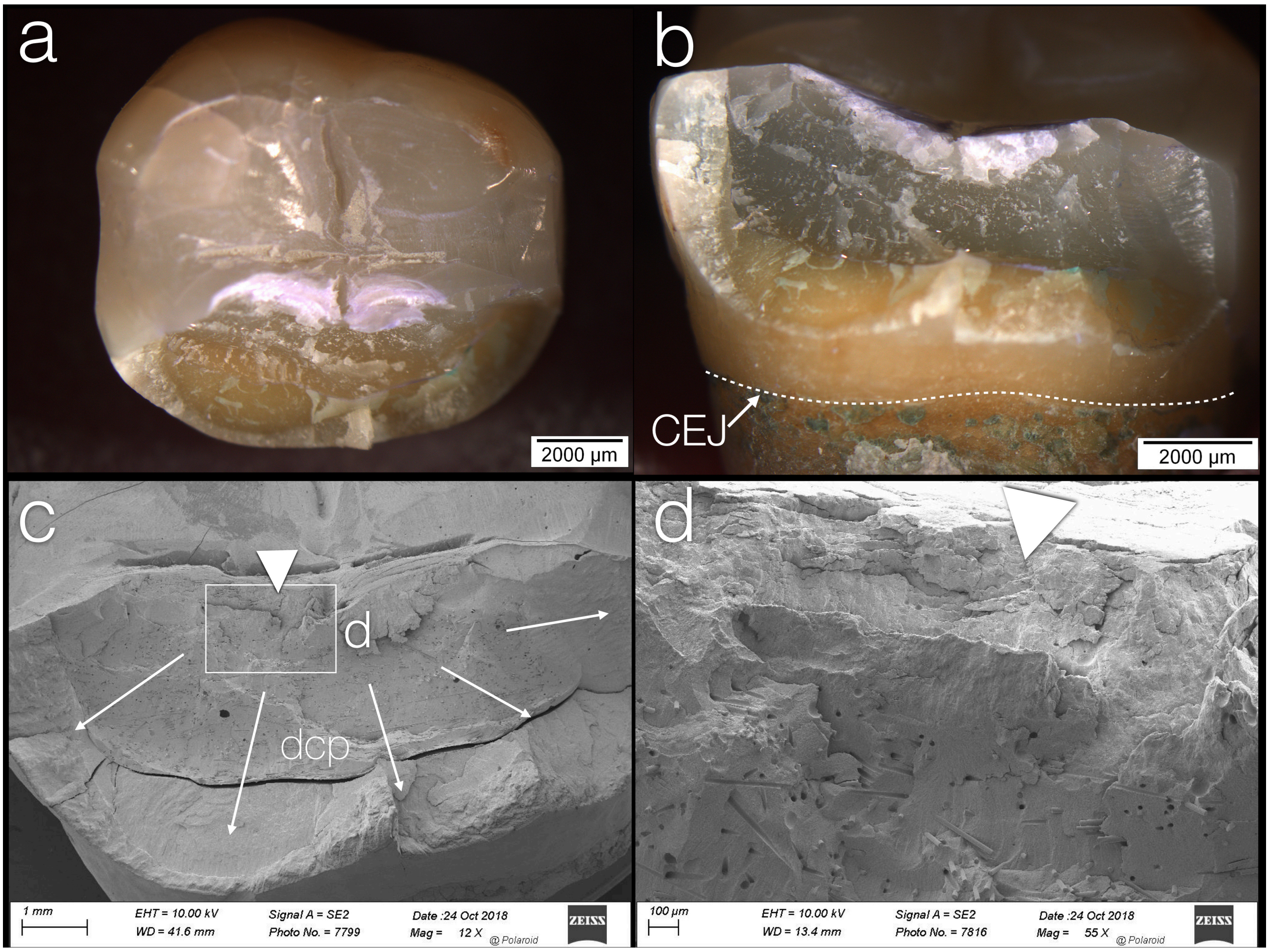


Fig. 8. An example of reparable fractured of specimen (Group B). (a) Stereomicroscope image of the pattern of the fracture on occlusal side. (b) Stereomicroscope image of the pattern of the fracture in buccal side sowing a fracture over the CEJ, marked with dotted line. (c) Hackle lines are clearly visible in the SEM picture and they indicate the direction of crack propagation (dcp, white arrows). The white rectangle d in (c) represents (d). (d) An high magnification of the contact area where the origin was located and marked by a white triangle.

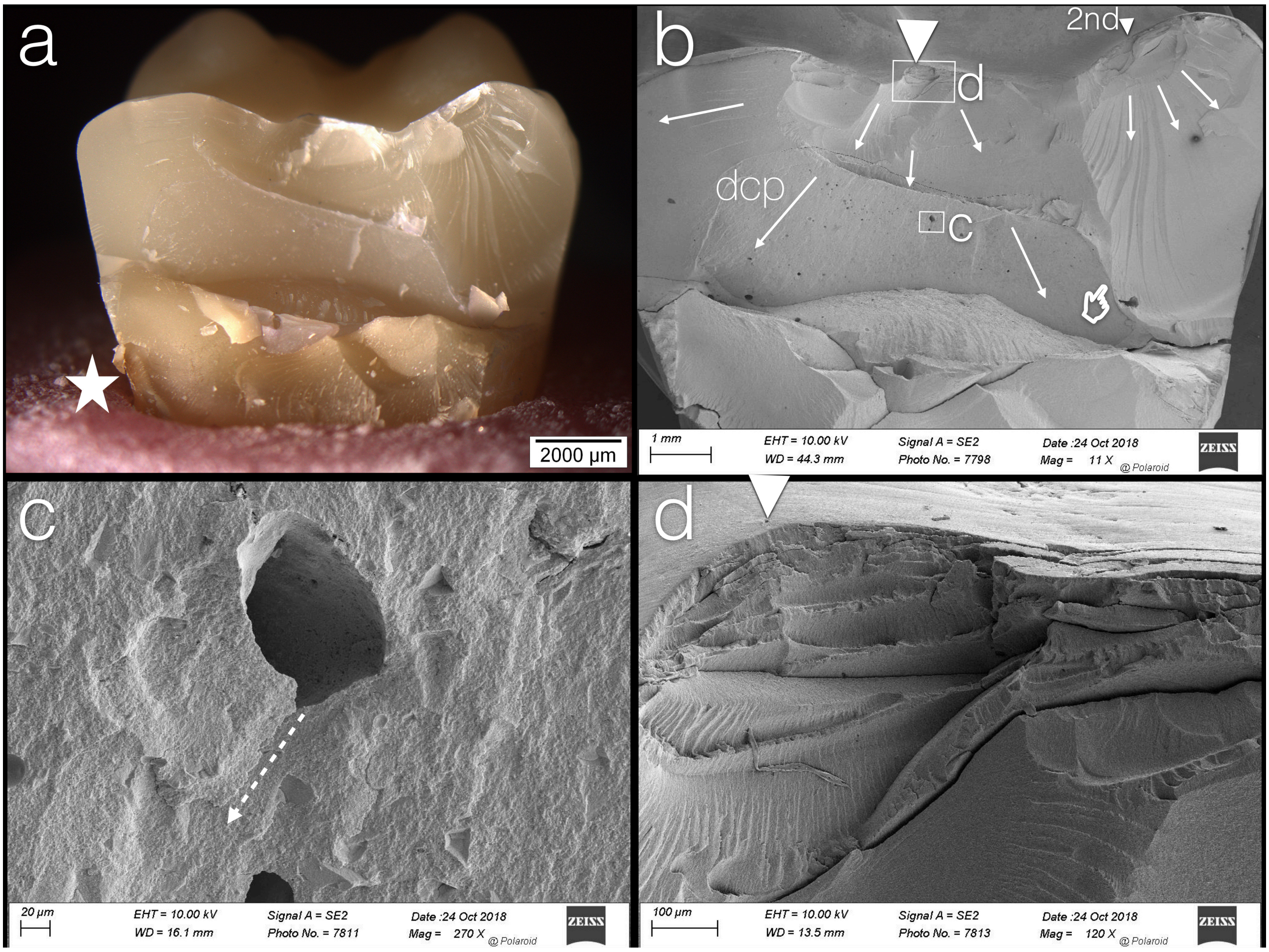


Fig. 9. An example of unrepairable fracture of specimen (Group A). (a) Stereomicroscope image of the pattern of the fracture. The fracture ended at the level of the vestibular mesial root, where it produced a “compression curl” (white star). (b) Scanning electron microscope (SEM) image showing the fracture. The white hand indicates the “arrest line” of a secondary event of the fracture. Hackle lines (white arrows) show the direction of the crack propagation. The white rectangle c in (b) represents (c). The white rectangle d in (b) represents (d). (c) Presence of a defect in the resin material which determined the formation of a wake hackle during the spreading of the fracture. this features confirmed the downward direction of the crack propagation (whit dotted arrow) (d) An high magnification of the contact area where the origin was located and marked by a white triangle.

Chapter 3: Discussion

Discussion

Recently, glass fibers have been inserted into the resin-based materials used in prosthodontics to improve their mechanical properties, or to splint and stabilize teeth [Strassler et al. 2007]. The evolution of dental engineering has allowed for insertion of fibers into endodontic posts, thus improving the aesthetic and mechanical properties of endodontically treated teeth and reducing the risk of catastrophic root fractures. Laboratory research has demonstrated that fibers can also be inserted into resin composites to improve the mechanical properties of direct and indirect adhesive restorations [Lassilla et al. 2016]. The most recent development in fiber-reinforced composites (FRCs) was the introduction of short FRC materials [Bijelic-Donova et al. 2016, Lassilla et al. 2016], which show better mechanical properties than other resin composite materials. However, few studies have evaluated their utility in direct composite restoration.

The present study aimed to investigate the mechanical properties of FRCs, and their potential application to direct restorations. In particular, the effects of FRCs on flexural strength, marginal adaptation to cavity margins, and fracture resistance when applied to direct composite restorations of endodontically treated teeth, were evaluated.

In the first study, inserting glass fibers into commercial composites did not increase flexural strength, although the everX resin composite, which contains short fibers, had significantly better bending strength compared with the tested composite resin. Several studies have compared the properties of FRCs with conventional composites [Bijelic-Donova et al. 2016, Garoushi et al. 2013, Goracci et al. 2014, Abouelleil et al. 2015], showing that the insertion of resin composite fibers significantly improved their mechanical properties.

In the present study, flexural strength and flexural modulus were analyzed using a three-point bending test according to the ISO 4049 standard. Bar-shaped specimens having dimensions of $2 \times 2 \times 25$ mm^3 were prepared using a Teflon® mold between two glass slabs. The testing appliance was made of two high-speed cobalt-steel rods (diameter: 2 mm) mounted in parallel with a 20-mm gap between supports. Each specimen was loaded at its center with a cylindrical-ended striker (diameter: 2 mm). A universal testing machine was operated at a crosshead speed of 1 mm/min until specimen failure occurred. For the fracture toughness test, rectangular bar specimens of dimensions $2 \times 5 \times 25$ mm^3 were prepared, and a sharp central notch was produced before loading into the universal testing machine.

Bijelic-Donova et al. [2016], Goracci et al. [2013], and Garoushi et al. [2013] showed that the flexural strength of everX Posterior FRC was significantly better than that of conventional composites. However, in the present study, the insertion of glass fibers into conventional composites specimens did not significantly improve the flexural strength. These data disagree with Garoushi et al. [2013], who showed that E-glass fiber insertion into a resin composite improved this property. Huang et al. [2018] compared a new short S2-glass fiber composite with everX and a bulk-fill flowable material (SDR). They found that while the S2-glass composite had better flexural strength than the everX composite, it had a lower flexural modulus than the SDR composite. These inconsistencies may be related to interactions of the different glass fibers within the composites, and to the application of different compressive forces [Rocca et al. 2013].

The enhanced material properties were attributed to stress transfer from the matrix to the fibers, and to the action of the fibers in mitigating crack propagation through the material. Bijelic-Donova et al. [2016] studied the mechanical properties of everX Posterior and showed that fracture toughness and flexural strength were improved by incorporating millimeter-scale short fibers and developing a semi-interpenetrating network (semi-IPN) structure. An IPN is the combination of thermoset (crosslinked) and thermoplastic (linear) phases within a single matrix. Moreover, those authors showed that the fibers stretched, thus deflecting crack propagation, and also induced a closure force on the crack and reduced stress intensity at the crack tip. During crack bridging, discontinuous fibers would likely stretch between the edges of the propagating crack, thereby decreasing notch sensitivity and causing blunting of the initially sharp crack. This would lower the stress concentration at the crack tip and possibly slow down or impede the crack propagation [Bijelic-Donova et al. 2016]. This explanation agrees with Abouelleil et al. [2015], who showed that samples created with fiber insertion remained connected after fracture toughness and flexural strength testing.

Silanization with methacrylate-based silane, which is compatible with both methacrylates and dimethacrylates, also improved the mechanical properties of FRCs. The presence of polymethylmethacrylate (PMMA) within the semi-IPN structure, which reduced the stiffness of the crosslinked resin monomer, likely contributed to the toughening effect. The bridge-creating capacity depended on the fiber length. Only the longer fibers could create bridges, which increased fracture resistance and fracture energy. Previous studies [Bijelic-Donova et al. 2016, Garoushi et al. 2013, Goracci et al. 2014, Abouelleil et al. 2015] showed that the optimal physico-mechanical properties were obtained with formulations between 8.5 and 10 V_f%, according to the equation:

$V_f\% = (W_f/\rho_f)/(W_f/\rho_f) + W_m/\rho_m$

where V_f% is the volume fraction expressed as a percentage, W is the weight fraction (weight %), ρ is the density, and f corresponds to the fiber and m to the matrix [Bijelic-Donova et al. 2016].
For this reason, each FRC had a specific critical fiber length. The optimum fiber length for a composite reinforced with short fibers was 1.2-times the critical fiber length. Moreover, Huang et al. [2018] considered the aspect ratio of discontinuous glass fibers and demonstrated that the critical fiber length could be as much as 50 times the fiber diameter.

The studies conducted for the present thesis evaluated resin composites reinforced with glass fibers in direct posterior restorations. All tests were performed on extracted teeth that were treated endodontically. Experiments were conducted using endodontically treated teeth because this restoration type is a major area of concern in dentistry. Biomechanical analysis of endodontically treated teeth clarified that the coronal destruction due to dental caries, and the loss of marginal ridge integrity, decreased tooth rigidity and, thus, fracture resistance [Tamse et al. 1998, Tamse et al. 1999, Assif et al.1994]. Several studies have established that endodontically treated teeth typically fail due to marginal leakage or coronal fracture [Baba et al. 2014, Manocchi et al. 2011, McComb 2008].

The specimens selected for study in this thesis were posterior teeth: lower molars in Studies #2 and #4, and upper premolars in Study #3. The endodontically treated premolars were more likely to fail. During the chewing cycle, they are loaded with compressive and transaxial forces, which can lead to progressive weakening of the coronal structure. Moreover, premolars often display a low crown:root ratio, which drastically worsens restoration prognosis and outcomes [Schwartz and Robbins 2004]. Mandibular molars were selected because they are the teeth most frequently subjected to endodontic treatment, and are often extracted because of secondary caries and cusps, or radicular fractures. In such cases, a restoration technique capable of reinforcing the weakened remaining tooth structure is of fundamental importance for reducing the likelihood of fractures [Scotti et al. 2016].

In the present study, mesio-occlusal-distal (MOD) cavities were prepared to decrease fracture resistance as much as possible, and to better evaluate the reinforcement effectiveness of the tested techniques. Clinically, a MOD cavity in a posterior tooth is the most difficult cavity type to rehabilitate endodontically. Several studies have shown that MOD preparation and endodontic treatment amplified the stress inside the tooth, mainly due to the loss of marginal ridges [Reeh et al. 1989, Mondelli et al. 1980, Tang et al. 2010], and increased the resistance to cuspal fracture [Smith et al. 1997, Gelb et al. 1986, Joynt et al. 1987, Pilo et al. 1998]. Thus, the ideal rehabilitation of an endodontically treated tooth should improve mechanical resistance by reinforcing the weakened remaining tooth structure, to prevent unfavorable fracture outcomes, and, ideally, restore the strength of the intact tooth.

The clinical survival of endodontically treated posterior teeth depends on several parameters such as restoration type, occlusal load, lateral excursive contacts, and remaining tooth structure [Reeh et al. 1989, Assif et al. 1994]. The thickness of the residual cavity walls represents a simple but effective parameter for clinical evaluation of the remaining tooth structure, and consequently informs the selection of the most appropriate type of restoration and material [Scotti et al. 2013].

The results of the present study show that glass fiber insertion within direct composite restorations generally increased the fracture resistance of endodontically treated teeth, although the results related to fracture strength are conflicting. Moreover, it is notable that none of the direct restoration techniques assessed in these studies could restore the fracture resistance to the level of a sound tooth.

Intraorally, these teeth are subjected to cyclic loading through mastication; dental restorations most commonly fail as a result of fatigue, where coronal fracture represents the final event of the cyclic loading process. Thus, it is important to evaluate the interfacial behavior of adhesive restorations after fatigue tests.

Occlusal stresses generated during mastication, and especially during parafunctional activities such as bruxism, have a deleterious effect on the marginal adaptation of composites [Qvist et al. 1983], especially at gingival margins where occlusal forces tend to be concentrated [Francisconi et al. 2009]. These mechanical stresses, when repeated over time, lead to fatigue or weakening of the interface, and once the concentrated stresses exceed the interfacial fracture toughness, a crack can form that on its own may lead to further gap formation and microleakage [De Munck et al. 2005].

Several in vitro methods are available to evaluate marginal gaps, most of which involve using dyes as tracers. These penetration methods typically require the soaking of a prepared tooth in a suitable dye solution, followed by sectioning through the restoration and assessing the leakage that has occurred using light microscopy, scanning electron microscopy (SEM), or autoradiography. The extent of leakage can be quantified using a length scale, but the degree of leakage is graded by operators according to a predetermined range of values. One of the main disadvantages of this method is that it only provides a qualitative assessment, namely, confirmation of the presence or absence of dye in the section studied. A variant of this approach uses a nonparametric scale, which provides a semiquantitative score according to the degree of dye penetration. Dye and tracer samples can only be examined in the plane through which they were sectioned.

X-ray micro-computed tomography (μCT) is a relatively new technique used to detect interfacial gaps. X-rays nondestructively penetrate through the specimen and are collected slice-by-slice by a detector. This two-dimensional information is processed using specific algorithms, and three-dimensional reconstruction is then performed. The number of studies using μCT in restorative dentistry is increasing, as this technique has proven effective for evaluating the internal adaptation of composite resin restorations [Zeiger et al. 2009, Kakaboura et al. 2007, Sun et al. 2009, Hirata et al. 2015], magnitude and direction of polymerization shrinkage [Cho et al. 2011, Van Ende et al. 2015], and interfacial leakage (silver nitrate infiltration) [Carrera et al. 2015, Zhao et al. 2014]. The present study used a SkyScan 1172 Micro-CT instrument (Bruker) to evaluate the marginal integrity of post-endodontic restorations.

The results described in the present thesis reveal how the insertion of fibers into the resin composite can significantly reduce the increase in marginal gap caused by cyclic fatigue. This reduction is equivalent or better to that achieved by the composite overlay. A gap may form due to polymerization shrinkage and failure to obtain a strong bond. Terzvergil et al. [2006] compared the polymerization shrinkage strain of glass fibre-reinforced (GFR) and particulate filler composites; the FRCs showed lower microleakage scores compared with the particulate filler composite. Thus, as reported by Garoushi et al. [2013], the material will not be able to shrink along the length of the fibers during polymerization of an FRC.

Subsequent occlusal stresses generated during mastication, and especially during parafunctional activities such as bruxism, have a deleterious effect on the marginal adaptation of composites [Qvist et al. 1983], especially at gingival margins where occlusal forces tend to concentrate [Francisconi et al. 2009]. These mechanical stresses repeated over time lead to the fatigue or weakening of the interface. Once the concentrated stresses exceed the interfacial fracture toughness, a crack can form, which can lead to gap formation and microleakage [De Munck et al. 2005]. However, within the oral cavity, materials are subjected to mechanical, thermal, and chemical processes that induce fatigue. Damage progresses from substructural and microscopic changes to the formation of microscopic cracks, structural instability and, finally, complete fracture [Suresh et al. 1991]. Thus, interfacial analysis is crucial to better understand the kinetics of biomechanical failure. A limitation of the present study was the lack of thermal stress application, where such stress can contribute to intraoral temperature changes and exert effects on the composite–tooth interface. Thermal stress can arise because composites and adhesives have higher thermal contraction/expansion coefficients than hard tooth tissues [Gale et al. 1999].

Currently, a conservative restoration approach is preferred to preserve sound tissue, the presence of which is directly related to the fracture resistance of a tooth. The present findings clearly reveal how a direct composite restoration can significantly improve the fracture resistance of endodontically treated teeth having MOD cavities. A significant reinforcement effect was obtained by insertion of a glass-fiber post within the direct composite restoration. Fiber post insertion within a composite restoration can improve the ability of the tooth–restoration complex to absorb the occlusal loads along the major axis of the tooth [Panitvisai et al. 1995], thereby increasing its resistance to occlusal loads [Mohammadi et al. 2009]. With a lower cuspal deflection, the possibility of marginal leakage, which creates a gap at the tooth–restoration interface with consequent marginal infiltration, is reduced [Acquaviva et al. 2011]. Favorable outcomes of fiber post-supported composite restorations, with respect to post-endodontic restoration longevity, have been reported in several in vivo studies [Scotti et al. 2015, Mannocci et al. 2005]. Nevertheless, some in vitro studies showed how endodontically treated premolars without fiber post placement had fracture toughness similar to those in which a fiber post was inserted. Krejci et al. [1998] confirmed that restorations avoiding post-space preparation, and thus sacrificing less residual sound tissue, might show greater resistance to fracture regardless of the degree of impairment of the dental structure. Another study [Soares et al. 2008] concluded that the use of glass-fiber posts did not reinforce the tooth restoration complex. A less invasive restorative solution, i.e., use of FRC restorations, could solve the problem of overpreparation in post-endo restorations.

Fracture strength is measured via a static test to predict the likelihood of failure of restored teeth under compression [Taha et al. 2014]. To evaluate the distribution of occlusal and masticatory loads on molar crowns, forces are usually applied to the central pit, and parallel [Fu et al. 2010] or obliquely [Jiang et al. 2010] along the dental axis. However, recent studies demonstrated that during maximum intercuspidation in the second phase of chewing, stresses are more concentrated along the cervical dental portion and mesiolingual radicular area of the mandibular molars [Benazzi et al. 2011]. Jiang et al. [2010] used a finite-element model to analyze stress concentration in vital and endodontically treated mandibular molars restored with indirect adhesive restorations. Samples were subjected to a vertical or 45° oblique occlusal load (constant load of 45 N) to simulate a masticatory load. In all specimens subjected to the lateral load, the stress was mainly concentrated along the cervical radicular portion of the tooth, at the floor of the preparation, and at the loading site. Therefore, in the present study, samples were subjected to a lateral load delivered at a 45° angle to distribute the stress within areas having a higher fracture risk.

Short FRCs are expected to enhance the longevity of medium-to-large-sized composite restorations in posterior teeth [Frater et al. 2014], because the fracture toughness of short-fiber composite resins is generally higher than that of conventional composite resins [Garoushi et al. 2013, Manhart et al. 2000, Drummond et al. 2004]. This property is attributed to the millimeter-scale short fibers, which exceed the critical fiber length [Vallittu et al. 2015] and facilitate stress transfer from the matrix to the fibers. Furthermore, the presence of fibers results in an anisotropic characteristic [Vallittu et al. 2014] that may relieve stress and prevent crack propagation. However, significant improvement in fracture resistance using direct techniques tested without glass-fiber insertion was associated with a slight but significant increase in the load resistance, independent of the composite material used. Notably, none of the restoration techniques tested could restore the fracture resistance to that of a sound maxillary premolar.

In the present study, glass fibers were inserted within a direct composite restoration to better understand their effects on fracture resistance and crack propagation. In all cases, a significant increase in fracture resistance was seen; the strengthening effect was comparable to that obtained with fiber-post insertion. The presence of glass fibers within the resin composite likely altered the elastic modulus of the material itself, thus modifying the stress distribution and transmission to residual cavity walls. These results are consistent with previous studies [Belli et al. 2016, Kemaglu et al. 2005] showing that use of polyethylene fibers in composite restorations, for root-filled teeth with large MOD preparations, yielded statistically enhanced fracture resistance relative to resin composite restorations. The authors of those studies suggested that the polyethylene fibers had a stress-modifying effect along the restoration–dentin interface, and the bonding ability of fibers in combination with the resin might have increased the fracture strength of the tooth by keeping both cusps together. However, Rodrigues et al. [2010] concluded that fibers placed into MOD cavities do not reinforce teeth, although they may protect against fracture propagation toward the pulp chamber floor. These inconsistencies could be related to the different angles at which the specimens were loaded. An insignificant effect of fiber reinforcement was also reported by Rocca et al. [2015]. Bidirectional E-glass fibers were placed over the pulpal chamber area, as in the present study, but indirect Lava Ultimate overlays were used to restore endodontically treated molars. No statistically significant improvement in fracture resistance was found when glass fibers were placed in the buccal–palatal direction. The connection of the residual walls of the specimens through the fibers may offset the compressive load that induced tension in the cervical area. A similar effect was noted by Karzoun et al. [2015], who placed a horizontal fiber post in a post-endodontic composite restoration, thereby joining the palatal and buccal walls of the MOD cavity. This technique increased the fracture resistance, although the horizontal post did not eliminate catastrophic fractures [Nicola et al. 2016].

Different results were obtained in experiments conducted on premolar teeth (Study #3) and molar teeth (Study #4): the fracture resistance was not significantly improved by glass fiber insertion into the MOD cavity. Another experiment revealed how the insertion of fibers had a positive effect on the fracture resistance of lower molars, as also occurs with the insertion of a fiber post. The differences in results can be attributed to several factors. First, the variation in occlusal anatomy among the tested restorations may have affected the outcomes. An occlusal anatomy characterized by abundant grooves, and with triangular ridges of different inclinations, can cause differences in the propagation of loading forces discharged onto occlusal surfaces during tests. Additionally, the samples prepared in the various studies underwent several preliminary treatments before the fracture resistance was evaluated. Study #2 used a thermal fatigue test associated with a mild mechanical fatigue test. Meanwhile, Study #3 instead evaluated samples after a more intense chewing simulation, while Study #4 did not include a cyclic fatigue test.

Study #3 showed that significant improvements in fracture resistance associated with the direct techniques applied without glass-fiber insertions also led to a slight but significant increase in load resistance, independent of the composite material used.

However, the literature indicates that short FRCs enhance the longevity of medium-to-large-sized composite restorations in posterior teeth [Frater et al. 2014], because the fracture toughness of the short-fiber composite resins is generally higher than that of conventional composite resins [Garoushi et al. 2013, Manhart et al. 2000, Drummond et al. 2004]. This behavior was attributed to the millimeter-scale short fibers, which exceeded the critical fiber length [Vallittu et al. 2015] and facilitated stress transfer from the matrix to the fibers. Furthermore, the presence of fibers results in anisotropy [Vallittu et al. 2014], which may relieve stress and prevent crack propagation.

Moreover, the results reported herein showed that insertion of glass fibers into direct composite restorations did not statistically increase the fracture resistance of endodontically treated upper premolars. Rodrigues et al. [2010] found that fibers placed into MOD cavities did not reinforce teeth because the cusp deflection strength was derived from the adhesive system and composite resin, and not from the inserted glass fibers, which instead could protect against fracture propagation toward the pulp chamber floor. Also, Cobankara et al. [2008] reported no difference in outcome between resin composite restorations with and without fibers, in MOD cavities in molars. Luthria et al. [2012] found no statistically significant differences among a standard composite, composite impregnated with glass fiber, and composite impregnated with polyethylene fiber, but the fracture resistance of the GFR composite was higher, similar to the present study.

As in the present thesis, an insignificant effect of fiber reinforcement under overlay restorations was reported by Rocca et al. [2015], who placed bidirectional E-glass fibers over the pulpal chamber area of devitalized molars restored with CAD/CAM resin composite overlays.

Fennis et al. [2005] obtained similar results: use of the GFR composite did not increase the load-bearing capacity of premolars with cusp-replacing restorations. This may be related to the overlay thickness serving as an indirect measurement of the distance between the glass fiber and the loading impact area. In fact, Oskoee et al. [2009] reported that fracture resistance increased when fibers were placed close to the point where force was exerted, because it led to a shorter working arm and to lower input force, in accordance with Archimedes' law of the lever,. Additionally, placing fibers on the occlusal surfaces kept the buccal and lingual cusps together, resulting in higher fracture resistance. Thus, placing glass fibers in the cervical to middle thirds did not significantly increase fracture resistance.

In the present experiments, glass fibers were inserted in the buccal–oral direction (u-shaped), similar to the method suggested by Belli et al. [Belli et al. 2005, Belli et al. 2006]. The form and direction of fibers, their composition, fiber/resin volume ratio, and the bond strength between fibers and resin influenced the reinforcing effect. Moreover, the mechanical properties of the composite depend on the type, extension, and length of the fibers [Belli et al. 2006, Samadzadeh et al. 1997]. Belli et al. [2006] showed that the use of polyethylene ribbon fibers in composite restorations increased fracture resistance, due to the ability of the fibers to connect the residual walls and modify stress transmission and distribution along the restoration–dentin interface. However, that study was conducted on molars that were not subjected to cyclic loading before fracture. A similar effect was reported by Karzoun et al. [2015]: They placed a horizontal fiber post into a post-endodontic composite restoration, joining the palatal and buccal walls of an MOD cavity. This technique improved the fracture resistance, although the horizontal post did not eliminate catastrophic fractures.

Even the horizontal insertion of unidirectional glass fibers did not significantly influence the fracture resistance of lower molars. In Study #4 of this thesis, a fiber network (everStick) was inserted within the direct restoration filled with a commercial short glass fiber composite (everX Posterior). The direct restoration with everX Posterior had similar fracture resistance to that of a composite overlay.

Cuspal replacement restorations should be performed with due consideration of the preservation of tooth structure and the type of restorative material used. Among several available aesthetic treatment options, resin composites and bonded ceramic restorations are more conservative than full-coverage porcelain-fused-to-metal crowns, which require additional removal of sound tooth tissue [Edelhoff et al. 2002]. The development of adhesive-based integrated restorations has enabled preservation of the maximum amount of sound tooth tissue [Ferracane et al. 2011]. The use of these restorations is recommended to minimize stress concentration and tensile stress in the remaining tooth structure. In teeth with limited tissue loss, direct and indirect adhesive restoration techniques can enhance the internal strength of the tooth structure without occlusal capping [Mohammadi et al. 2009, Fokkinga et al. 2005]. Thus, the rehabilitation of endodontically treated teeth showing considerable loss of tissue must involve complete or partial crown coverage.

These results are inconsistent with those of Study #3 in this thesis, but the difference in the teeth selected, and the absence of any aging procedure before conducting the fracture resistance test, could explain the discrepancy. Notably, the specimens' geometric dimensions were different. After pulpal chamber opening, the volume of the remaining tooth structure in molars is approximately 2.5-times that of premolars. Moreover, the anatomy of maxillary premolars with two roots that are not fused at the cervical third close to root canals gives rise to a small amount of dentine supporting the furcation. Additionally, the load inclination used for premolars causes stress to be concentrated in the cervical area of the buccal cusp and the furcation area, which in turn concentrates stress in regions with smaller volumes of dentine structure [Castro et al. 2012].

A previous finite-element analysis conducted by Lin et al. [2008] showed that the amount of stress in the restorative material and remaining tooth structure was mainly influenced by the restorative material used and the cavity design. When cuspal-coverage treatment is considered, the cuspal height should be reduced to at least 1.5 mm, to significantly decrease the stress [Chang et al. 2009]. The use of restorative material with low modulus of elasticity, such as resin composites, was associated with more favorable biomechanical performance for restorations involving cuspal replacement, because of reduced load transmission to the underlying tooth structure [Brunton et al. 1999].

The present experiments also revealed that the fracture load of cuspal-covered teeth was not statistically significantly higher than that of teeth restored with composite intracuspal direct restoration when an FRC was used. The results regarding cusp splinting in composite restorations suggest the possibility of decreasing the fracture caused by cuspal deflection even without cusp coverage. Mohammadi et al. [2009] confirmed these findings, showing that root-filled maxillary premolars, restored with direct resin composite with or without fiber posts and cusp capping, had similar fracture resistance under static loading.

Fractography analysis was performed on selected samples in Studies #2 and #4. Fractography permits accurate failure analysis through observation of the microscopic fracture surface. It can reveal the direction of crack propagation, and helps elucidate the origin or cause of failure.

The fracture pattern was determined using a combined stereomicroscopy and SEM technique. The stereomicroscope revealed the entire surface of the fractured specimens, while SEM

images provided information on fractography markers, such as hackle lines, arrest lines, and compression curl, which are indicators of the crack propagation direction.
Fractures may occur due to critical stress concentration, cyclic fatigue caused by stress corrosion, or a combination of mechanisms involving processing methods and restoration design. Typically, fractography analysis is performed on a recovered portion of the fractured material;, if the analysis is performed accurately, the information obtained may disclose relevant processing or design problems, such that measures can be taken to avoid similar failures in the future. In this way, the development or improvement of materials, in terms of their manufacturing and design, handling, laboratory grinding results, and finishing/polishing procedures can be realized.

A fractographic analysis of the pattern of a fragment provides important information concerning when a cohesive fracture occurs. In adhesive fractures, most of the features of the crack, such as its origin, the "mirror", and the "hackles", are not visible. The end of the fracture event is indicated by the presence of a "compression curl" on the cracked roots of the specimens, indicating that the fracture originated from an upper region. Some secondary cohesive fractures can also be recognized [Scotti et al. 2016, Cesar et al. 2017]. In Study #2, denuded fibers left a mark on the surface of the build-up after debonding (see Figure 3). This indicated that the front part of the fracture was partially deviated after coming into contact with the layer of fibers, following their horizontal direction. However, this effect was insufficient to avoid a catastrophic break; the charged wall was always deflected toward the point of fracture.

The fractographic analysis performed in Study #4 revealed that for all of the specimens, the primary crack front originated from the occlusal surface of the restoration, i.e., from the major contact loading area, and then propagated downward through the entire restoration.
Specimens mainly showed failure modes characterized by two kinds of crack paths:

- A restorable path (see Figure 8): the fracture originated at the occlusal surface and ran through the restoration, but not to the center of the teeth. Stereomicroscope images showed that the crack terminated at the buccal or lingual surface, and over the cementoenamel junction (CEJ).
- A non-restorable path (see Figure 9): the fracture ran through the restoration vertically and terminated below the CEJ, thus splitting the tooth. SEM revealed that the crack (dcp) ran from the top of the restoration to the tooth cavity (see Figure 9b).

Fracture types were distinguished based on failure mode (see Figure 7). Most of the fracture in Groups 1, 3, and 4 were nonrepairable, while Group 2 contained mainly repairable fractures. The data showed a lack of influence of a continuous bidirectional fiber net (everStick) on fracture propagation, but everX could partially deviate cracks. This contrasts with the studies of Vallittu et al. [1999] and Garoushi et al. [2006], who showed that bidirectional glass fiber provided better fracture toughness than short glass fiber. However, these studies were not conducted on natural teeth, but rather on silicon-molded specimens.

On the contrary, an insignificant effect of fiber reinforcement on fracture propagation was reported by Rocca et al. [2015]. Bidirectional E-glass fibers were placed over the pulpal chamber area, as in the present study, but indirect Lava Ultimate overlays were used to restore endodontically treated molars. The results of the present study are in agreement with those of Acquaviva et al. [2011], Lassilla et al. [2016], and Nakayama et al. [1974]. They reported that a GFR composite containing short glass fibers decreased cuspal deflection and shrinkage stress, which likely resulted in a more favorable fracture pattern upon loading of the samples. In Rocca et al. [2016], the main crack originated from the contact area subject to the highest load; the difference in tooth anatomy between their study and the present investigation could have caused the discrepancy in the results.

References

Abouelleil H, Pradelle N, Villat C, Attik N, Colon P, Grosgogeat B. Comparison of mechanical properties of a new fiber reinforced composite and bulk filling composites. Restor Dent Endod. 2015 Nov;40(4):262–70.

Acquaviva PA, Madini L, Krokidis A, Gagliani M, Mangani F, Cerutti A. Adhesive restoration of endodontically treated premolars: Influence of posts on cuspal deflection, J Adhes Dent. 2011;13: 279–286.

Assif D, Gorfil C. Biomechanical considerations in restoring endodontically treated teeth. J Prosthet Dent. 1994 Jun;71(6):565–7.

Baba N, Goodacre C. Restoration of Endodontically Treated Teeth: Contemporary Concept and Future Perspectives. Endodontic Topics 2014;31:68–83.

Belli S, Erdemir A, Ozcopur M, Eskitascioglu G. The effect of fibre insertion on fracture resistance of root filled molar teeth with MOD preparations restored with composite. Int Endod J. 2005 Feb;38(2):73–80.

Belli S, Erdemir A, Yildirim C. Reinforcement effect of polyethylene fibre in root-filled teeth: Comparison of two restoration techniques. Int Endod J. 2006 Feb;39(2):136–42.

Benazzi S, Kullmer O, Grosse IR, Weber GW. Using occlusal wear information and finite element analysis to investigate stress distributions in human molars. J Anat. 2011;219(3):259–272.

Bijelic-Donova J, Garoushi S, Vallittu PK, Lassila LV. Mechanical properties, fracture resistance, and fatigue limits of short fiber-reinforced dental composite resin. J Prosthet Dent. 2016 Jan;115(1):95–102.

Bijelic-Donova J, Uctasli S, Vallittu PK, Lassila L. Original and repair bulk fracture resistance of particle filler and short fiber-reinforced composites. Oper Dent. 2018 Sep/Oct;43(5):E232–E242.

Brunton PA, Cattell P, Burke FJ, Wilson NH. Fracture resistance of teeth restored with onlays of three contemporary tooth-colored resin-bonded restorative materials. J Prosthet Dent. 1999 Aug;82(2):167–71.

Carrera CA, Lan C, Escobar-Sanabria D, Li Y, Rudney J, Aparicio C, Fok A (2015) The use of micro-CT with image segmentation to quantify leakage in dental restorations Dent Mater. 2015;31(4):382–390.

Castro CG, Santana FR, Roscoe MG, Simamoto PC Jr, Santos-Filho PC, Soares CJ. Fracture resistance and mode of failure of various types of root-filled teeth. Int Endod J. 2012 Sep;45(9):
Cesar PF, Della Bona A, Scherrer SS, Tholey M, van Noort R, Vichi A, Kelly R, Lohbauer U. ADM guidance–Ceramics: Fracture toughness testing and method selection. Dent Mater. 2017 Jun;

Chang YH, Lin WH, Kuo WC, Chang CY, Lin CL. Mechanical interactions of cuspal-coverage designs and cement thickness in a cusp-replacing ceramic premolar restoration: A finite-element study. Med Biol Eng Comput. 2009 Apr;47(4):367–74.

Cho E, Sadr A, Inai N, Tagami J. Evaluation of resin composite polymerization by three dimensional micro-CT imaging and nanoindentation. Dent Mater. 2011;27(11):1070–1078.

Cobankara FK, Unlu N, Cetin AR, Ozkan HB. The effect of different restoration techniques on the fracture resistance of endodontically treated molars. Oper Dent. 2008 Sep–Oct;33(5):526–33.

De Munck J, Van Landuyt K, Peumans M, Poitevin A, Lambrechts P, Braem M, Van Meerbeek, B. A critical review of the durability of adhesion to tooth tissue: Methods and results. J Dent Res. 2005;84:118–32.

Drummond JL, Lin L, Miescke KJ. Evaluation of fracture toughness of a fiber containing dental composite after flexural fatigue. Dent Mater. 2004;20:591–9.

Edelhoff D, Sorensen JA. Tooth structure removal associated with various preparation designs for posterior teeth. Int J Periodontics Restorative Dent. 2002;22(3):241–249.

Fennis WM, Tezvergil A, Kuijs RH, Lassila LV, Kreulen CM, Creugers NH, Vallittu PK. In vitro fracture resistance of fiber reinforced cusp-replacing composite restorations. Dent Mater. 2005 Jun;21(6):565–72.

Ferracane JL. Resin composite–State of the art. Dent Mater. 2011;27(1):29–38.

Fokkinga WA, Le Bell AM, Kreulen CM, Lassila LVJ, Vallittu PK, Creugers NHJ. Ex vivo fracture resistance of direct resin composite complete crowns with and without posts on maxillary premolars. Int Endod J. 2005;38:230–237.

Francisconi LF, Graeff MS, Martins Lde M, Franco EB, Mondelli RF, Francisconi PA, et al. The effects of occlusal loading on the margins of cervical restorations. J Am Dent Assoc. 2009; 140:1275–82.

Frater M, Forster A, Kereszturi M, Braunitzer G, Nagy K. In vitro fracture resistance of molar teeth restored with a short fibre-reinforced composite material. J Dent. 2014;42:1143–1150.

Fu G, Deng F, Wang L, Ren A. The three-dimensional finite-element analysis of stress in posterior tooth residual root restored with postcore crown. Dent Traumatol. 2010;26(1):64–69.

Gale MS, Darvell BW. Thermal cycling procedures for laboratory testing of dental restorations. J Dent. 1999 Feb;27(2):89–99.

S.K. Garoushi, L.V.J. Lassila, A. Tezvergil, P.K. Vallittu, Load bearing capacity of fibre-reinforced and particulate filler composite resin combination, J. Dent. 2006;34:179–184.

Garoushi S, Säilynoja E, Vallittu PK, Lassila L. Physical properties and depth of cure of a new short fiber-reinforced composite. Dent Mater. 2013 Aug;29(8):835–41.

Gelb MN, Barouch E, Simonsen RJ. Resistance to cusp fracture in Class II prepared and restored premolars. J Prosthet Dent. 1986 Feb;55(2):184–5.

Goracci C, Cadenaro M, Fontanive L, Giangrosso G, Juloski J, Vichi A, Ferrari M. Polymerization efficiency and flexural strength of low-stress restorative composites. Dent Mater. 2014 Jun;30(6):688–94.

Hirata R, Clozza E, Giannini M, Farrokhmanesh E, Janal M, Tovar N, Bonfante EA, Coelho PG. Shrinkage assessment of low shrinkage composites using microcomputed tomography. J Biomed Mater Res B Appl Biomater. 2015;103(4):798–806.

Huang Q, Qin W, Garoushi S, He J, Lin Z, Liu F, Vallittu PK, Lassila LVJ. Physicochemical properties of discontinuous S2-glass fiber-reinforced resin composite. Dent Mater J. 2018 Jan 30;37(1):95–103.

Jiang W, Bo H, Yongchun G, LongXin N. Stress distribution in molars restored with inlays or onlays with or without endodontic treatment: A three-dimensional finite-element analysis. J Prosthet Dent. 2010;103(1):6–12.

Joynt RB, Wieczkowski G Jr, Klockowski R, Davis EL. Effects of composite restorations on resistance to cuspal fracture in posterior teeth. J Prosthet Dent. 1987 Apr;57(4):431–5.

Kakaboura A, Rahiotis C, Watts D, Silikas N, & Eliades G. 3D-marginal adaptation versus setting shrinkage in light-cured microhybrid resin composites Dent Mater. 2007;23(3) 272–278.

Karzoun W, Abdulkarim A, Samran A, Kern M. Fracture strength of endodontically treated maxillary premolars supported by a horizontal glass fiber post: an in vitro study. J Endod. 2015 Jun;41(6):907–12.

Kemaloglu, H, Belli S, Erdemir A, Ozcopur M, Eskitascioglu G. The effect of fibre insertion on fracture resistance of root-filled molar teeth with MOD preparations restored with composite. Int. Endod. J. 2005;38:73–80.

Krejci I, Dietschi D, Lutz FU. Principles of proximal cavity preparation and finishing with ultrasonic diamond tips. Pract. Periodont. Aesthet. Dent. 1998;10:295–298.

Lassila L, Garoushi S, Vallittu PK, Säilynoja E. Mechanical properties of fiber-reinforced restorative composite with two distinguished fiber length distribution. J Mech Behav Biomed Mater. 2016 Jul;60:331–338.

Lin CL, Chang YH, Liu PR. Multi-factorial analysis of a cusp-replacing adhesive premolar restoration: A finite element study. J Dent. 2008 Mar;36(3):194–203.

Luthria A, Srirekha A, Hegde J, Karale R, Tyagi S, Bhaskaran S. The reinforcement effect of polyethylene fibre and composite impregnated glass fibre on fracture resistance of endodontically treated teeth: An in vitro study. J Conserv Dent. 2012 Oct;15(4):372–6.

Manhart J, Kunzelmann KH, Chen HY, Hickel R. Mechanical properties of new composite restorative materials. J Biomed Mater Res (Appl Biomater). 2000;53:353–61.

Mannocci F, Qualtrough AJ, Worthington HV, Watson TF, Pitt Ford TR. Randomized clinical comparison of endodontically treated teeth restored with amalgam or with fiber posts and resin composite: Five-year results. Oper. Dent. 2005;30:9–15.

Mannocci F, Bhuva B, Stern S. Restoring teeth following root canal re-treatment. Endodontic Topics 2011, 19, 125–152.

McComb D. Restoration of the endodontically-treated tooth. 2008

Mohammadi N, Kahnamoii MA, Yeganeh PK, Navimipour EJ. Effect of fiber post and cusp coverage on fracture resistance of endodontically-treated maxillary premolars directly restored with composite resin. J Endod. 2009;35(10): 1428–1432.

Mondelli J, Steagall L, Ishikiriama A, de Lima Navarro MF, Soares FB. Fracture strength of human teeth with cavity preparations. J Prosthet Dent. 1980;43:419–422.

Nakayama, WT, Hall DR, Grenoble DE, Katz JL. 1974. Elastic properties of dental resin restorative materials. J Dent Res. 53:1121–1126.

Nicola S, Alberto F, Riccardo MT, Allegra C, Massimo SC, Damiano P, Mario A, Elio B. Effects of fiber-glass-reinforced composite restorations on fracture resistance and failure mode of endodontically treated molars. J Dent. 2016 Oct;53:82–7.

Oskoee PA, Ajami AA, Navimipour EJ, Oskoee SS, Sadjadi J. The effect of three composite fiber insertion techniques on fracture resistance of root-filled teeth. J Endod. 2009 Mar;35(3):413–6.

Panitvisai P, Messer H, Cuspal deflection in molars in relation to endodontic and restorative procedures, J. Endod. 1995; 21:57–61.

Pilo R, Brosh T, Chweidan H. Cusp reinforcement by bonding of amalgam restorations. J Dent. 1998 Jul–Aug;26(5-6):467–72

Qvist V. The effect of mastication on marginal adaptation of composite restorations in vivo. J Dent Res. 1983;62:904–6.

Reeh ES, Messer HH, Douglas WH. Reduction in tooth stiffness as a result of endodontic and restorative procedures. J Endod. 1989 Nov;15(11):512–6.

Rocca GT, Rizcalla N, Krejci I. Fiber-reinforced resin coating for endocrown preparations: A technical report. Oper Dent. 2013 May–Jun;38(3):242–8.

Rocca GT, Saratti CM, Cattani-Lorente M, Feilzer AJ, Scherrer S, Krejci I. The effect of a fiber-reinforced cavity configuration on load-bearing capacity and failure mode of endodontically-treated molars restored with CAD/CAM resin composite overlay restorations. J Dent. 2015 Sep;43(9):1106–1115.

Rocca GT, Sedlakova P, Saratti CM, Sedlacek R, Gregor L, Rizcalla N, Feilzer AJ, Krejci I. Fatigue behavior of resin-modified monolithic CAD-CAM RNC crowns and endocrowns. Dent Mater. 2016 Dec;32(12):e338–e350.

Rodrigues FB, Paranhos MP, Spohr AM, Oshima HM, Carlini B, Burnett Jr. LH. Fracture resistance of root-filled molar teeth restored with glass fibre bundles. Int Endod J. 2010 May;43(5):356–62.

Samadzadeh A, Kugel G, Hurley E, Aboushala A. Fracture strengths of provisional restorations reinforced with plasma-treated woven polyethylene fiber. J Prosthet Dent. 1997 Nov;78(5):447–50.

Schwartz RS, Robbins JW (2004) Post placement and restoration of endodontically treated teeth: A literature review. J Endod. 2004; 30(5):289–301.

Scotti N, Scansetti M, Rota R, Pera F, Pasqualini D, Berutti E, The effect of the post length and cusp coverage on the cycling and static load of endodontically treated maxillary premolars. Clin. Oral Invest. 2011;15:923–929.

Scotti N, Rota R, Scansetti M, Paolino DS, Chiandussi G, Pasqualini D, Berutti E. Influence of adhesive techniques on fracture resistance of endodontically treated premolars with various residual wall thicknesses. J Prosthet Dent. 2013 Nov;110(5):376–82. doi: 10.1016/j.prosdent.2013.08.001. Epub 2013 Oct 3.

Scotti N, Eruli C, Comba A, Paolino DS, Alovisi M, Pasqualini D, Berutti E. Longevity of Class 2 direct restorations in root-filled teeth: A retrospective clinical study. J. Dent. 2015;43:499–505.

Smith CT, Schuman N. Restoration of endodontically-treated teeth: A guide for the restorative dentist. Quintessence Int. 1997 Jul;28(7):457–62.

Soares PV, Santos-Filho PC, Martins LR, Soares CJ. Influence of restorative technique on the biomechanical behavior of endodontically treated maxillary premolars. Part I: Fracture resistance and fracture mode. J Prosthet Dent. 2008;99:30–37.

Strassler HE, Serio CL. Esthetic considerations when splinting with fiber-reinforced composites. Dent Clin North Am. 2007 Apr; 51(2):507–524.

Sun J, Eidelman N, Lin-Gibson S. 3D mapping of polymerization shrinkage using X-ray micro-computed tomography to predict microleakage. Dent Mater. 2009;25(3):314–320.

Suresh S. Fatigue and Materials, 2nd ed. Cambridge Solid State Science Series, 1991.

Taha NA, Palamara JE, Messer HH. Fracture strength and fracture patterns of root-filled teeth restored with direct resin composite restorations under static and fatigue loading. Oper Dent. 2014;39:181–188.

Tamse A, Zilburg I, Halpern J. Vertical root fractures in adjacent maxillary premolars: An endodontic-prosthetic perplexity. Int Endod J. 1998 Mar;31(2):127–132.

Tamse A, Fuss Z, Lustig J, Kaplavi J. An evaluation of endodontically-treated vertically-fractured teeth. J Endod. 1999 Jul;25(7):506–8.

Tang W, Wu Y, Smales RJ. Identifying and reducing risks for potential fractures in endodontically-treated teeth. J Endod. 2010 Apr;36(4):609–17.

Tezvergil A, Lassila LV, Vallittu PK. The effect of fiber orientation on the polymerization shrinkage strain of fiber-reinforced composites. Dent Mater. 2006 Jul;22(7):610–6. Epub 2005 Oct 18.

Vallittu, PK. Prosthodontic treatment with a glass fiber-reinforced resin-bonded fixed partial denture: A clinical report. J. Prosthet. Dent. 1999;82:132–5.

Vallittu PK. High-aspect ratio fillers: Fiber-reinforced composites and their anisotropic properties. Dent Mater. 2015;31:1–7.

Vallittu PK. High-aspect ratio fillers: Fiber-reinforced composites and their anisotropic properties. Dent Mater. 2014;(31):1–7.

Van Ende A, Van de Casteele E, Depypere M, De Munck J, Li X, Maes F, Wevers M, Van Meerbeek B. 3D volumetric displacement and strain analysis of composite polymerization. Dent Mater. 2015;31(4):453–61.

Zeiger DN, Sun J, Schumacher GE, Lin-Gibson S. (2009) Evaluation of dental composite shrinkage and leakage in extracted teeth using X-ray microcomputed tomography. Dent Mater. 2009;25(10) 1213–20.

Zhao XY, Li SB, Gu LJ, Li Y. Detection of marginal leakage of Class V restorations in vitro by micro-computed tomography. Oper Dent. 2014 Mar–Apr;39(2):174–80.

Chapter 5: Conclusion

Conclusions and Future Directions

Based on the studies included in this thesis, the following conclusions were drawn:

- The use of fiber inserted horizontally in a direct composite restoration didn't show a significant increment in mechanical properties, in particular flexural strength and fracture toughness test, performed on samples with direct composite restoration, didn't show any improvement of the value glass fiber groups.
- The insertion of horizontal glass-fibers seemed to reduce marginal Gap after cyclic loading
- Fractographic analysis showed that glass fibers with a buccal-palatal orientation partially deviated fracture, even if it did not prevent catastrophic fracture of the specimen.
- The use of short fiber resin composite (Ever X posterior) for direct restoration of endodontically treated teeth seemed to improve mechanical properties on flexural strength and fracture toughness, if samples were immediately loaded until fracture. Flexural strength values of samples aged with cyclic loading showed a decrement of fracture strength values for the Ever X direct restorations group.
- Fractographic analysis of short glass fiber samples seemed to showed more reparable fracture patter in comparison with commercial direct restoration. Ulterior studies had to be done to verify this date standardizing the surface of loading of the samples.

Further studies are needed to value Fiber Reinforced Composite behavior on marginal gap and fracture pattern, considering the anatomy of the occlusal surface and the design of the margin of the cavity.