The Usage of Short Fiber-Reinforced Composites to Restore Anterior and Posterior Teeth with Direct Restorative Techniques

PhD Thesis

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List of the publications providing the basis of, and related to the topic of the thesis

Publications providing the basis of the thesis:

I. **Sáry T**, Garoushi S, Braunitzer G, Alleman D, Volom A, Fráter M. Fracture behaviour of MOD restorations reinforced by various fiber-reinforced techniques - An in vitro study. J Mech Behav Biomed Mater. 2019 Oct;98:348-356. doi: 10.1016/j.jmbbm.2019.07.006.

II. **Sáry T**, Garoushi S, Braunitzer G, Alleman D, Volom A, Fráter M. Corrigendum to "Fracture behaviour of MOD restorations reinforced by various fiber reinforced techniques - An in vitro study" [J. Mech. Behav. Biomed. Mater. 98 (2019) 348-356]. J Mech Behav Biomed Mater. 2020 Feb;102:103505. doi:10.1016/j.jmbbm.2019.103505. Epub 2019 Nov 4. Erratum for: J Mech Behav Biomed Mater. 2019 Oct;98:348-356. PMID: 31694796.

III. Fráter M, **Sáry T**, Néma V, Braunitzer G, Vallittu P, Lassila L, Garoushi S: Fatigue failure load of immature anterior teeth: Influence of different fiber post-core systems. Odontology. 2020 May 2. doi: 10.1007/s10266-020-00522-y.

IV. Fráter M, **Sáry T**, Garoushi S. Bioblock technique to treat severe internal resorption with subsequent periapical pathology: a case report. Restor Dent Endod. 2020 Aug 18;45(4):e43. doi: 10.5395/rde.2020.45.e43.

Related publications:

- Forster A, **Sáry T**, Braunitzer G, Fráter M. In vitro fracture resistance of endodontically treated premolar teeth restored with a direct layered fiber-reinforced composite post and core. J Adhes Sci Technol. 2016;31:1454–66. https ://doi.org/10.1080/01694243.2016.12597 58.
- Balázs Szabó P., **Tekla Sáry**, Balázs Szabó. The key elements of conducting load to fracture mechanical testing on restoration-tooth units in restorative dentistry. Analecta Technica Szegedinensia. 2019. Vol. 13., No. 2. doi: 10.14232/analecta.2019.2.59-64
- Fráter M, **Sáry T**, Jókai B, Braunitzer G, Säilynoja E, Vallittu PK, Lassila L, Garoushi S. Fatigue behavior of endodontically treated premolars restored with different fiber-reinforced designs. Dent Mater. 2021 Mar;37(3):391-402. doi: 10.1016/j.dental.2020.11.026.
- Fráter M, **Sáry T**, Braunitzer G, Balázs Szabó P, Lassila L, Vallittu PK, Garoushi S. Fatigue failure of anterior teeth without ferrule restored with individualized fiber-reinforced post-core foundations. J Mech Behav Biomed Mater. 2021 Mar 3;118:104440. doi: 10.1016/j.jmbbm.2021.104440.
- Fráter M, **Sáry T,** Vincze-Bandi E, Volom A, Braunitzer G, Szabó P B., Garoushi S, Forster A. Fracture Behavior of Short Fiber-Reinforced Direct Restorations in Large MOD Cavities. Polymers 2021, 13, 2040. https://doi.org/10.3390/polym13132040

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List of Abbreviations

- bis-GMA: bisphenol-A-glycidyl methacrylate
- CEJ: cemento-enamel junction
- DC: degree of conversion
- DEJ: dentin-enamel junction
- ET: endodontically treated
- FRC: fiber-reinforced composite
- LWUHM: Leno Weave Ultra High Modulus
- MO: mesio-occlusal
- MOD: mesio-occluso-distal
- MTA: mineral trioxid aggregate
- OD: occluso-distal
- PMMA: polymethyl methacrylate
- SD: standard deviation
- semi-IPN: semi-interpenetrating polymer network
- SFRC: short fiber-reinforced composite
- TEGDMA: triethylene glycol dimethacrylate

Introduction

In the field of science, mimicry involves the reproduction or the copying of a model, a reference. If we, as dentists, want to replace what has been lost, we need to identify the correct reference. For the restorative dentist, this unquestionable reference is the intact natural tooth, since natural teeth – through their optimal combination of enamel and dentin – demonstrate the perfect and unmatched compromise between stiffness, strength and resilience. Restorative procedures and alterations in the structural integrity of teeth can easily violate this subtle balance [1].

The physiologic performance of intact teeth is the result of an intimate and balanced relationship between biological, mechanical, functional and esthetic parameters [1]. In modern dental practice, the restoration and the tooth should form a structurally adhesive and optically cohesive medium, which has the ability to withstand repetitive multi-axial biomechanical force loads over a prolonged period of time [2]. In the field of restorative dentistry, the term "biomimetic" defines the study of the structure and function of the tooth tissue as a model for the design and manufacturing of materials, and techniques to restore teeth [3]. In fact, the primary aims of biomimetic dentistry are to be as minimally invasive as possible, and to substitute the missing hard dental tissues with restorative materials closely resembling the natural tissues, as far as their mechanical features and properties are concerned. A typical biomimetic restorative approach is the combined use of artificial materials to replace different hard dental tissues, such as the use of porcelain to replace enamel and composite resins to replace dentin, combined with optimized bonding strategies. This construction is possible if an indirect treatment is chosen for restorative purposes. However, as logical as it might seem, the use of this approach is limited in practice, due to both financial and technical limitations [3]. In practice, the most challenging aspect is the ability to apply the various engineering concepts in the small biological structure of a tooth [4].

Esthetic dentistry continues to evolve through innovation in bonding systems, restorative materials and minimal invasive preparation designs. The increased use of composite materials in both anterior and posterior regions has made technological advances in this field necessary. In spite of the fact that both amalgam and composite resin are considered to be suitable materials for restoring Class I and Class II cavities in both premolar and molar teeth, resin composites have almost totally replaced amalgam as a restorative material in posterior teeth in many countries [5].

Magne et al. [6] showed that amalgam fillings in Class I and Class II cavities could not reinforce the tooth in an ideal way and could not substitute the missing dental tooth structure in terms of biomechanical features. Versluis et al. [7] found that an amalgam filling (which is normally unbonded) generated stresses in the tooth comparable to those which would have occurred if the cavity had been left unrestored. When loaded, the amalgam did not take over the load previously carried by the lost healthy tooth structure.

With the current phasedown of amalgam as a dental material [8], everyday clinicians are repeatedly faced with the question, whether a direct or an indirect restoration shall be chosen when planning to restore teeth as adequately as possible. Most frequently the replacement of lost tooth structure involves the usage of direct composite restorations. Further to the ability to bond to hard dental tissue, being mediated by adhesive systems, direct composite restorations feature the advantage of natural shade and are less expensive [9]. The reinforcement of the remaining dental hard tissue [10] and the adhesive properties allow a smaller cavity preparation compared to an indirect treatment [11]. This presents an economically more friendly option for patients, facilitating a faster treatment for the dental staff as well. It has been put forward in some studies [12,13] that the internal strength of teeth can be reinforced with the application of direct and indirect adhesive techniques. However, this ability highly depends on the given clinical situation and cavity parameters (see later).

Current dental composites have adequate mechanical properties for use in both anterior and posterior areas in the mouth. For anterior restorations, Lempel et al. [14] found satisfying clinical performance for direct composite resin restorations, with an annual failure rate of only 1.43% after a mean observation period of 7.2 years. The reasons for failures mostly included restoration fracture or chipping and color mismatch. The related studies that evaluated anterior fillings or direct veneers also found that esthetic failures were more common; more precisely they included color alteration, surface staining and marginal discoloration [15]. These would cause a negative perception of the restoration for the patient as well. Resin composite restorations in the posterior region have shown good overall clinical performance in small and medium sized fillings, with annual failure rates between 1-3 % [16]. Unlike the failure modes discussed with anterior composite fillings, secondary decay and fracture are among the most important reasons for clinical failure for restored posterior teeth [17]. The survival of direct posterior restorations strongly correlates with the size of the restoration. Bernardo et al. [18] reported an increase in the annual failure rate from 0.95 % for single surface to 9.43% for four or more surface restorations. Therefore, the larger the restorations, the more it shows a tendency to fail due to mechanical, fracture-related problems, resulting obviously in decreased longevity [19]. It seems that mechanical failure rates are higher in the posterior region than in the anterior region. Understanding these limitations and potential risk factors is crucial for the effective improvement and optimization of composite resin restorations [1].

It is known that both intact and restored teeth demonstrate cuspal flexure and coronal deformation when loaded. Both the direction and the extent of occlusal forces and loadings vary in the mouth according to the position of the teeth. This should be taken into account during the decision-making process of how to best restore the affected teeth [20]. Maxillary anterior teeth must withstand dominantly flexural and shear stresses. Due to their position in the dental arch, premolar teeth must withstand both flexural and compressive loads, resulting in mixed stress-loads. In general, molar teeth have to support mostly compressive loads that run parallel with the long axis of the tooth [21]. Regarding the extent of loading, occlusal forces may be relatively light and repetitive in normal mastication, relatively heavy and repetitive as seen in bruxism, and extremely heavy and sudden in case of trauma [22]. In anterior teeth, the mean maximum occlusal force was around 200 to 228 N. Another study reported a mean maximum occlusal force of 93 to 150 N for a white and 140 to 206 N for an indigenous Brazilian population for incisor teeth [23]. On the basis of these findings, a fracture resistance of approximately 180 to 200 N can be considered a safe evaluation threshold for a patient with no parafunctional habits. In the posterior region, forces range from 8 to 880 N during normal mastication, around 597 N for women and around 847 N for men on average [4]. Parafunctional loads can be even six times greater than the normal chewing force [24]. Extremely high loads have been described in bruxism, or when teeth in this region suffer trauma or the patient accidentally bites on a hard object (for example seeds, a stone in a salad or a walnut shell in a cake). Furthermore, the high prevalence of temporomandibular disorders leading to bruxism or clenching in modern Western societies definitely make it necessary to find restorative solutions that can withstand not only the normal, but the increased occlusal forces as well [25].

Biomechanical properties of short fiber-reinforced composite (SFRC) materials

Many studies have aimed to improve the mechanical properties of composite resins [26]. Fracture within the body and at the margins of restorations, polymerization shrinkage (see later) and secondary caries have been cited as major problems regarding the mechanical failure of posterior composites [27]. A Brunthaler article [17] proposed that fracture is more of an early failure mode, while secondary caries is more likely to be a long-term difficulty. Da Rosa et al. [28] and Pallesen et al. [29] carried out a long-term study (with more than 10 years of follow-up) which demonstrates that restoration failure was more frequently due to fracture than to caries in the posterior region. These findings suggest that bulk fracture is an important failure-mode regardless of the age or lifespan of the restoration. The fracture-related material properties – such as fracture resistance, deformation under occlusal load– have usually been evaluated by the determination of the basic material parameters: flexural strength and fracture toughness [30]. Fracture toughness is a mechanical property that describes the resistance of brittle materials to the catastrophic propagation of flaws under an applied load. It describes the damage tolerance of the material and can be understood as a measure for fatigue resistance [31]. Fracture toughness values are dependent on the mechanical properties and chemical composition of the individual component contained in the restorative material. If a material has high fracture toughness, it has the ability to better resist crack initiation and propagation. According to many, the property of fracture toughness and flexural strength has become the most important criteria regarding the longevity of dental materials, [32, 31].

From a biomimetic point of view, one should aspire to replace dentin with materials that have similar biomechanical properties [1]. Unfortunately the fracture toughness of microhybrid and nanohybrid composite resin materials are significantly lower than that of dentin [33]. Regarding the microstructure, composite resins consist of filler particles (generally not fibers) embedded in a resin matrix, whereas dentin consists of collagen fibers embedded in a hydroxyapatite matrix. Consequently, observing the microanatomy of the tissue itself, dentin should rather be seen as a fiber-reinforced composite instead of a particulate filler one [31]. Composite resins which are reinforced with millimeter scale short fibers show an interesting similarity to natural dentin, especially considering their microstructure and their biomechanical properties [34, 35].
Garoushi et al. measured that SFRC differed significantly and has superior fracture toughness (2.61 MPa $m^{1/2}$), flexural strength (114-124 MPa), and flexural modulus (9.5 GPa) compared to other tested bulk-fill or conventional composite resin materials. This was in accordance with Bijelic-Donova et al., who also investigated the correlation between the mechanical tests and the compressive fatigue limits of the examined resins [36]. The results showed that SFRC had a statistically higher fracture toughness and fatigue limit than conventional composite resins. The values showed a strong correlation between fatigue performance and the material's fracture toughness, and the SFRC was able to withstand both compressive static and fatigue loads [37, 36]. The authors declared that the toughening capability of SFRC over their competition materials

is due to two main factors: the millimeter-scale short fibers, which fulfill the critical fiber length measures, and the semi-interpenetrating polymer network (semi-IPN) structure.

It is important to note that all properties of fiber-reinforced composites are strongly dependent on a few specific parameters: **fiber orientation, fiber length, fiber diameter, fiber loading and aspect ratio**.

The **position and orientation** of the fibers within the structure is known to influence the structure's mechanical properties [38]. If the fibers are positioned unidirectionally – as in a conventional fiber post – the fiber reinforcement has an anisotropic property. This means that the reinforcing effect will change according to the direction of the loading. When loading is applied perpendicular to the long axis of the unidirectionally oriented fibers, maximal reinforcement occurs. Forces result in matrix-dominated failures if applied parallel to the long axis of the fibers [39]. When fibers are located in two distinct directions in one material (e.g.: everStickNET, GC Europe, Leuven, Belgium), the material is orthotopic and produces reinforcement in two directions, however, this reinforcement is less in one certain direction compared to anisotropic materials. Contrary to the above mentioned, an isotropic material has the same mechanical properties in every direction. This can be achieved by randomly oriented fibers, lending the material a reinforcing effect regardless of the orientation of the force, although reinforcement per direction is less effective, since a certain volume of fibers is divided into multiple directions [40].

The two most common types of fibers used in dentistry are S- and E-glass fibers (the "S" stands for "structural" and the "E" for "electric"). Aside from dental application, A, AR, C, D, E-CR and R-glass fibers are also manufactured. E-glass fibers contain borosilicate glass, as opposed to the aluminium-silicate and magnesium-oxide used in S-glass fibers. S-glass fibers undoubtedly have the highest tensile strength among all types, but also a relatively higher Young's modulus and consequently higher rigidity. E-glass fibers have demonstrated several advantages, such as its lower Young's modulus, thanks to which it is more elastic and easier to adapt to irregular shapes like root canals. It also has the ability to withstand tensile stresses and hold the potential to stop crack propagation in composite materials [7]. The aforementioned SFRC (everX Posterior, GC Europe, Leuven, Belgium) restorative material is intended to be used in high stress bearing areas especially in molars to withstand random range forces. It consists of a combination of a resin matrix (24 w%), randomly orientated E-glass fibers (9 w%) and inorganic particulate fillers (67 w%). The resin matrix contains bisphenol-A-glycidyl methacrylate (bis-GMA), triethylene glycol dimethacrylate (TEGDMA) and polymethyl methacrylate

(PMMA) forming a matrix called the semi-IPN which provides good bonding properties and improves the toughness of the polymer matrix [41].

The transfer of stress from the polymer matrix to the fibers is the foundation of the effective reinforcement SFRC has shown so far. This transfer is either possible if the fibers have a length equal to or greater than the **critical fiber length** and/or they show an ideal fiber **aspect ratio**, in the range of 30–94 [42]. The aspect ratio is the fiber length to fiber diameter ratio (l/d), and it affects the tensile strength, flexural modulus, and the reinforcing efficiency of the SFRC [43]. The critical fiber lengths of E-glass short fibers with bis-GMA polymer matrix vary between 0.5 and 1.6 mms [43]. Deterioration or initially poor adhesion between the fibers and polymer matrix increases the critical fiber length [43]. It has also been concluded that the critical fiber length should be as much as 50 times the **diameter** of the fiber for advanced fiber reinforced composites [43]. Garoushi et al. have shown that millimeter-scale short fiber fillers could stop the crack propagation and could provide an increase in the fracture resistance of SFRC [34]. Garoushi et al. also evaluated various available SFRC materials (Alert, EasyCore, Build-It, TI-Core, and everX Posterior) and found that all of the listed materials' fiber lengths fall below the critical measures except for everX Posterior, explaining why this composite resin had higher fracture toughness values [42].

Fibers impede the extension of a crack and develop interlocking bridges behind the progressing crack, dissipating energy by fiber pull-out, thus resulting in graceful rather than catastrophic failure. This might be due to the random orientation and the formation of a fiber network, which seemed to have enhanced the ability of the material to resist the fracture propagation, as well as to reduce the stress intensity at the crack tip from which a crack propagates in an unstable manner. As a consequence, the flexural properties and fracture toughness are increased. However, if the adhesion is not strong and if any voids appear between the fiber and the matrix, these voids may act as initial fracture sites in the matrix and may facilitate the failure of the material, explaining the significance of this bond [43].

Polymerization, depth of cure in SFRC materials

When using light cured resin materials for direct restorations, one must consider the dimensions of the cavity, since the light curing intensity decreases with the depth in the material. The intensity of light at a given depth and for a given irradiance period is a critical factor in determining the extent of reaction of monomer into polymer, typically referred to as the degree of conversion (DC). This feature is significantly associated with values of mechanical properties, biocompatibility, color stability and would therefore be expected to be associated with the clinical success of the restoration [43]. It has been documented that the degree of monomer conversion of resin-based composites influences their mechanical properties, and consequently the clinical performance as well [25]. Additionally, microhardness is considered a strong indication to the DC of the material.

Miletic and colleagues [44] associated the DC and the Vickers hardness and translucency parameter with the depth of cure of SFRC and different commercial bulk-fill composites. Miletic and Goracci et al. [45] both reported similar results, i.e. that SFRC had a significantly higher translucency than other tested bulk-fill materials, and measured a depth of cure of 5.09 mms. After 20 seconds of curing 4 mm specimens, SFRC showed bottom-to-top hardness ratios above 80%, suggesting this 4 mm depth to be the clinically advised thickness. Miletic et al. [44] as well as Garoushi et al. [46] attributed this performance to the millimeter-scale fibers which conduct and scatter the light better than particulate fillers. It has been demonstrated that refraction indices and extinction coefficients change during the polymerization of methacrylate monomer systems of the SFRC, which enhance light-induced polymerization [47]. The mentioned depth of cure has been confirmed by other studies as well [48, 49].

Polymerization shrinkage of SFRC materials

Polymerization shrinkage is one of the most critical limitations of light cured composite resins. In the relevant studies, volumetric shrinkage of the resin composites averages from 1.5 to 6% [50]. Such shrinkage induces contraction stress at the interface between the composite and the cavity walls leading to gap formation and a predisposition for secondary caries [51]. Countless studies can be found which aim to develop a solution for this problem. One option is to use the incremental technique, however, this proved to be time consuming as well as creating voids in-between the layers. Also, it still remains a question whether layering could adequately reduce the stress at all [52, 53]. Another option is to use bulk-fill materials [46], granting reduced polymerization shrinkage and faster application time, which all-in-all could reduce chairside time. Garoushi et al. [46] studied the polymerization shrinkage of several commercial posterior composite resins, including bulk-fill and SFRC resins using the strain gage method. They pointed out that SFRC had the lowest shrinkage strain (0.17%) and credited this to the short fiber fillers and plasticization of the polymer matrix. The short random fibers of the SFRC provide an isotropic reinforcing effect when placed in bulk. Nevertheless, the originally isotropic material could become anisotropic from the aspect of polymerization shrinkage when applied in incremental

layers of 1-2 mm thickness, if the fibers are aligned in the plane of application. In the aforementioned study, Garoushi et al. clarified that anisotropic materials' properties vary according to the orientation of reinforcing fibers, and shrinkage is not equal in all directions, as the polymerization shrinkage is controlled in the direction of the fibers [46]. Consequently, during polymerization, the material is not able to shrink along the length of the fibers and retains its original dimensions horizontally; nonetheless, the polymer matrix between the fibers can still shrink. Corresponding studies that tested SFRC, bulk-fill and composite resins by Tsujumoto et al. [54] and Bocalon et al. [55] seemed to have come to the same conclusion, i.e. that the presence of fiber fillers significantly reduces polymerization shrinkage (range of 30-72%.) [56].
In another study, Garoushi et al. evaluated the impact of SFRC on polymerization shrinkage strain, shrinkage stress, and marginal microleakage of the restoration [34]. They found that the presence of short fibers in the composite resin increases resistance to microcracking, while significantly decreasing shrinkage stress and microleakage compared to those restorations made from non-fiber-reinforced composite resins [34].

Recently, a new flowable SFRC (everX Flow, GC Europe, Leuven, Belgium) was introduced as a restorative material. This composite resin is also intended to be used as a dentin-replacing material in high stress bearing areas, especially in large cavities of vital and non-vital posterior teeth, similar to its predecessor, namely the packable SFRC. Due to its flowable consistency, it holds the promise of easy adaptability in limited spaces (e.g., root canals). It consists of a combination of a resin matrix, randomly orientated E-glass microfibers and inorganic silanated particulate fillers [57]. Its improved handling characteristics have resulted in an increased popularity among flowable conventional and flowable bulk-fill composites so far [58].
This flowable SFRC was reported to exhibit improved mechanical properties regarding flexural strength (171 MPa) and fracture toughness (2.88 MPa $m^{1/2}$) in comparison even to the packable SFRC (everX Posterior). This increased fracture toughness is attributed to the unique amount of fibers and simultaneously being able to reach the desired aspect ratio (30-94) to fulfill reinforcement. While the packable SFRC contains millimeter-long (0.7-2 mm) fibers, the fibers in the flowable SFRC are micrometer-long (0.2-0.3 mm) shifting the index to an ideal range regarding aspect ratio. This characteristic made it possible to incorporate an extreme number of fibers (25 w%) into this composite material.

Biomimetic usage of SFRC materials for restorative purposes

As the previously discussed data show, composites are not always the ideal materials for dentin replacement, especially in high stress bearing areas. Efforts have been made to reinforce these compromised resin restorations utilizing fiber reinforcement in order to increase the strength and toughness [59, 60, 61, 62, 63, 64]. In order to simplify the clinical technique for using fiber-reinforced composite (FRC) materials inside cavities, SFRC was introduced as a dentin-replacing material to support the remaining tooth structure and improve the durability of the final biomimetic composite restoration [65].

When choosing a restorative treatment, it is crucial to assess the depth and the dimension of the cavity in the tooth. The restorative approach should be in strict correspondence with the amount of remaining sound tissue.
Class I cavities in vital (i.e. endodontically not treated) premolar and molar teeth weaken the coronal structure by about 5-20 %, meaning that there is generally enough sound hard tissue left for a direct composite restoration, and no extra strengthening is needed according to Reeh et al. [66]. It remains a question whether a deep Class I molar cavity after root canal treatment would benefit from incorporating SFRC into the direct restoration [67]. In Class II mesio-occlusal (MO) or occluso-distal (OD) cavities however, losing one of the marginal ridges results in an approximately 45% decrease in coronal strength. The thickness of the remaining marginal ridge (and also of the buccal and oral walls) is critical, as it is the only component left naturally splinting the remaining walls together, therefore becoming an important factor in determining the valid restorative options for this situation. For a direct restoration the remaining ridge has to be at least 1 mm thick, providing the expected connecting effect [68]. This can also be seen in cuspal flexure values. Panitsvai et al. [69] studied cuspal deflection in molar teeth with MO/OD and mesio-occluso-distal MOD cavities in relation to endodontic and restorative treatment. For teeth with MO cavities their numbers show a cuspal deflection of 7.5 microns whereas in the case of (MOD) cavities, it was more than double: 16.5 microns. Gonzalez-Lopez [70] and El-Helali et al. [71] found similar relations: a standardized MOD cavity preparation in maxillary premolar teeth was shown to result in 63% average loss in relative cuspal stiffness, which is related principally to the loss of marginal ridge integrity [72, 22.]
Fráter et al. found that "shallow" (3-3.5 mm deep) MOD cavities can safely be restored with either a composite filling or an SFRC substructure covered with packable composite material in terms of fracture resistance [73]. However, it should be highlighted that even in the case of a shallow MOD cavity, normal composite filling resulted in unfavorable fractures when fracture occurred, whereas the usage of SFRC substructure led to dominantly repairable fractures.

Not only the dimension but also the depth of the cavity is a notable factor that determines how the stress will be distributed in the remaining structure. Forster et al. [74] prepared molar teeth with 3, 5, and 7 mm deep MOD cavities, which were restored with direct composite fillings. According to their results, the 3 mm deep composite restoration had adequate mechanical properties, most likely thanks to the rather large amount of sound tissue offering sufficient stability. An interesting finding was that the fracture resistance of the 5 and 7 mm deep groups restored with composite weren't significantly different. It shall be noted that teeth with the 5 mm cavity rates were not treated endodontically, while the 7 mm deep ones were endodontically treated (ET) teeth. More importantly, the fractures within this study were all non-restorable. This study highlights the need for further investigation among direct restorative options for a more optimal solution in case of deep MOD cavities in vital (non-endodontically treated) posterior teeth.

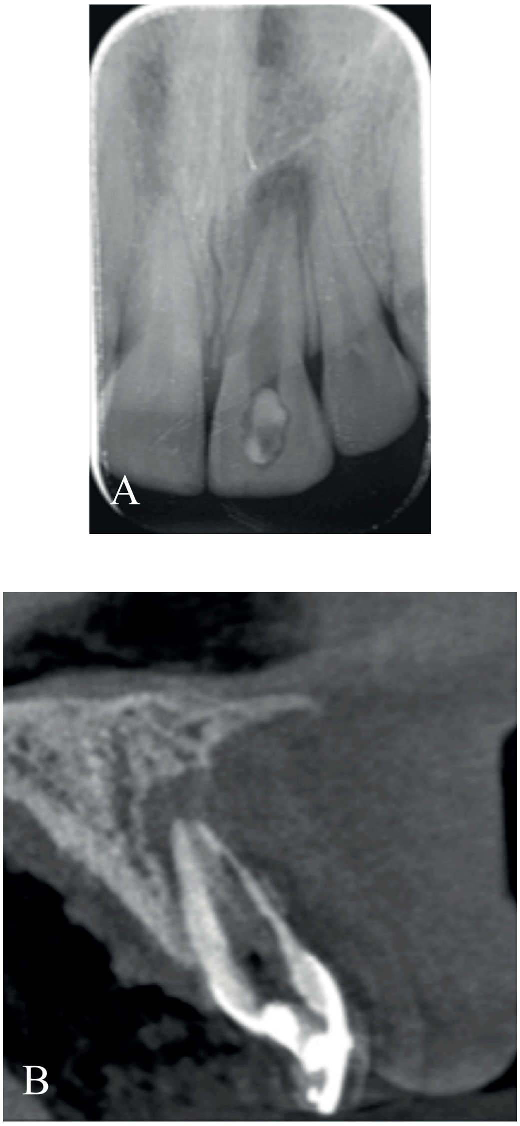
SFRC materials can also be used in case of ET teeth. Foster et al. examined ET premolar teeth with Class I cavities, comparing the mechanical properties of a traditional fiber post with other post-core reinforcement techniques, one of them being a direct-layered SFRC technique. According to their results, this technique showed no significant difference compared to natural intact teeth regarding fracture resistance. At this point the packable SFRC was layered in approximately 2 mm thick increments into the root canal (in the prepared post space) and subsequently into the coronal cavity as well. This technique was later simplified into a "3-step technique", using the packable SFRC up to 4-5 mm thick layers, filling up the mentioned cavities driven by anatomy till the lost dentin-enamel junction (DEJ). This method was later published as the Bioblock technique. The Bioblock technique produced significantly higher fracture resistance compared to FRC post restorative techniques in ET premolar teeth with MOD cavities, however, it was not yet able to reinforce to the extent of intact teeth [75]. These results are partly in accordance with other studies, for example by Garlapati and Gürel. Garlapati et al. [76] tested the fracture resistance of ET premolars with MOD cavities restored with different core materials, finding that the teeth restored with SFRC showed a more favorable failure mode and higher fracture resistance than teeth restored with other tested materials. Gürel et al. [77] also investigated ET premolars and their fracture strength when reinforced with an SFRC core. Again, these restorations showed higher fracture resistance values and more restorable fracture types than the other tested build-ups. These are corresponsive with the results of Eapen at al. showing that when ET premolar MOD cavities are restored with SFRC, the fracture resistance is significantly higher compared to other tested direct restorative techniques, including composite fillings [78]. Furthermore, their specimen containing SFRC build-ups were not different in terms of fracture resistance from intact teeth, which is contrary to the findings of Fráter el al. in this aspect [75]. Ozsevik et al. investigated ET molars with MOD cavities and found that SFRC layered under a composite coverage had mechanical values similar to those of natural intact teeth and higher than those restored with a conventional composite filling [79]. This is in line with the findings of Kemaloglu et al. [80] . Garoushi examined the static load-bearing capacity of biomimetic restorations compared with conventional and bulk-fill techniques [41, 81]. The biomimetic restoration with the SFRC substructure had the highest load-bearing capacity compared to other direct composite restorations. All in all, looking at a mechanically majorly weakened situation, e.g. an ET tooth with Class II MOD cavity, several studies have found that teeth with extensive tissue loss can be restored in a more favorable manner by combining SFRC with conventional composites rather than utilizing conventional composites alone [75, 80, 82].This alternative method could provide a solution to reduce the incidence of fatal fractures and cracks in ET teeth with MOD cavities.

However, the literature on SFRC does not show complete unanimity. Atalay [83], Barreto [84], and Rocca et al. [85] have not found such outstanding results for SFRC materials. Moreover, according to their research, the SFRC core does not improve the mechanical resistance of direct restorations made in extensive cavities. The discrepancies in their research results could most likely be explained by the differences in the used adhesive technique, by the thickness of the conventional composite covering the SFRC substructure and by the ways of performing the mechanical testing.

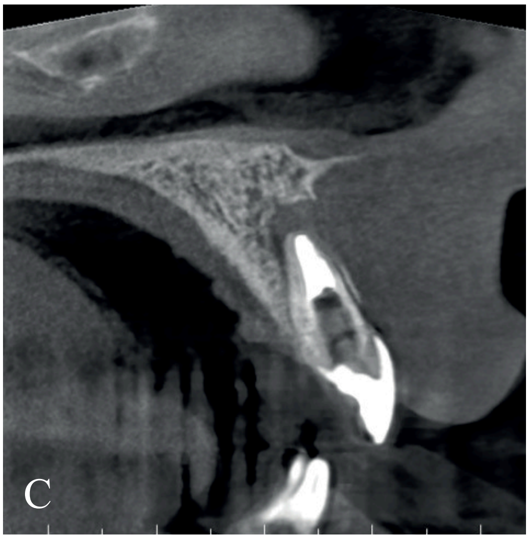
SFRC materials have also been used in anterior restorations, mainly in case of destructed ET anterior teeth. Bijelic et al. found that SFRC placed inside the root canal of anterior teeth and used as a core build-up proved to provide higher fracture resistance compared to a composite build-up with or without an FRC post [86]. This is in accordance with Garoushi et al. who found that a direct post-core made from SFRC performed better compared to FRC post and composite cores [87]. Furthermore, SFRC was able to shift the fracture pattern towards favorable ones whenever used in ET anterior teeth [87]. This is only partly confirmed by Fráter et al., however, in the cited study anterior ET teeth were tested without ferrule [88].

The author believes that the Bioblock technique can be a clinically valid potential solution for individualized fiber-reinforcement in ET teeth. It can also be extremely useful in the restorative treatment of internal resorptions or any major canal irregularities, widenings (e.g. anterior teeth with an open apex). The author has presented a case report of the successful restoration of a traumatized upper central incisor that was weakened due to severe internal root resorption and subsequent periapical lesion formation in order to present the Bioblock technique under in vivo conditions as well.

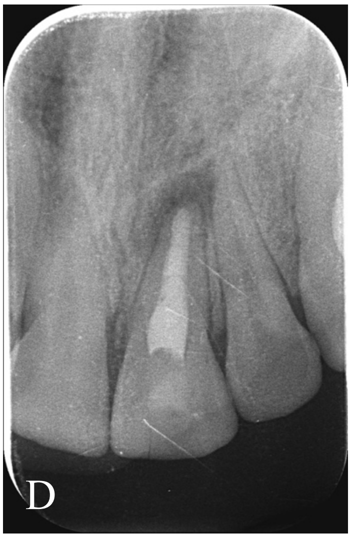
The case is only discussed briefly here.



Images of the patient's tooth upon presentation. (A) X-ray image upon presentation. (B) Cone-beam computed tomography image of the tooth upon presentation.

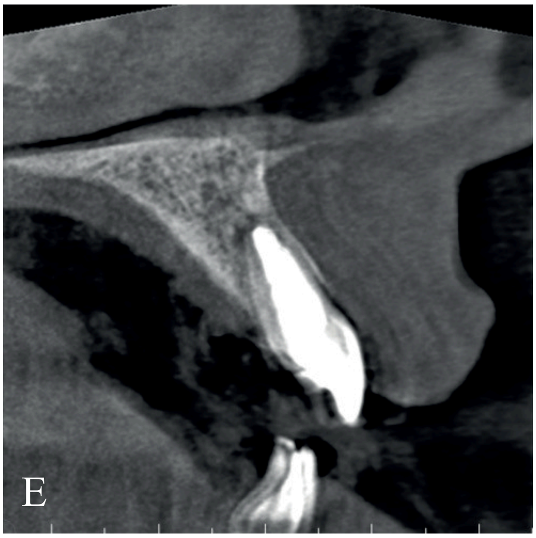


Cone-beam computed tomography image after the establishment of the apical mineral trioxide aggregate (MTA) plug (C).



X-ray taken at the appointment of completing of the coronal restoration. Some healing has already occurred in the periapical region (D).

During the making of the „Bioblock" in this specific case, the root canal was adhesively treated with a dual-cure self-etch adhesive system and was filled with SFRC (EverX Posterior, GC Europe) to the point of the root canal orifice. During this procedure, an approximately 4-mm-thick increment of SFRC material was placed in the root canal and applied to the most apical part to make contact with the MTA plug. This can be accomplished by pressing alternately with any small-headed microbrush or a periodontal probe or plugger. After the first layer appeared to be in position, a light-transmitting FRC post (1.4 mm GC Fiber Post, GC Europe) was inserted into the canal to facilitate the transmission of the light to the apically-positioned layers. The light-transmitting post was withdrawn 0.5–1 mm from the surface of the uncured SFRC layer so as not to directly contact it. The first layer of SFRC was light-cured through the post for 80 seconds using a light source with an average power density of 900 mW/cm^2. The application of SFRC was continued to the level of the cemento-enamel junction (CEJ). The coronal cavity was filled with composite resin for esthetic reasons.



Follow-up cone-beam computed tomography scan taken 1 year after the finalization of root canal treatment, showing the homogeneity of the short-fiber reinforced composite inside the canal (E).

Summarizing the literature mentioned above, it can be concluded that SFRC materials show outstanding quality in terms of fibers, polymers and mechanical and physical properties as well. As a result, it promises to be an excellent solution in direct biomimetic restorations if a previously lost, significant amount of dentin tissue is replaced with SFRC and covered with conventional composite resin with appropriate thickness.

The question arises whether or not vital (endodontically not treated) molar teeth with deep MOD cavities could also be reinforced with SFRC or other fiber-reinforced materials. Furthermore, it is worth investigating whether the Bioblock technique utilizing the packable or the newer flowable SFRC could be more useful in case of teeth after one-shot apexification.
The purpose of the proposed in vitro molar investigation was to assess the reinforcing effect of different FRC materials compared to polyethylene ribbon fibers combined with conventional composites using direct restorative techniques applied in Class II deep MOD cavities.
The purpose of the proposed in vitro anterior investigation was to assess the fatigue resistance and failure mode of simulated immature teeth after one-shot apexification, restored with different FRC materials. In addition, the curing performance was also investigated within the root

canal for each restorative option, regarding the difference in depth and adaptation of the material.

The null hypotheses were the following:
1. the anterior apexified teeth restored with different techniques would not differ regarding their fatigue resistance from intact teeth,
2. the anterior apexified teeth restored with different techniques would not differ in terms of their failure mode from intact teeth,
3. the molar teeth restored with the tested restorative techniques would show similar mechanical resistance as intact molar teeth,
4. the fracture patterns in molar teeth with deep class II cavities would not depend on the applied restorative technique.

Material and Method

All procedures of the investigations presented were approved by the Regional Ethics Committee for Human Medical and Biological Research (University of Szeged, Hungary) and the studies were designed in accordance with the Declaration of Helsinki (ID number: 4029).

Sample selection

For the **anterior** study, four hundred upper bovine incisors were collected and stored in 0.5% chloramine-T. The largest oro-vestibular and mesio-distal dimension and the height of the coronal portion from the CEJ were measured. The oro-vestibular and mesio-distal dimensions of the root part were also measured. As per these measurements, only the teeth with a maximum deviation of 10% from the determined mean were included in this study (a sum of one hundred-eighty teeth).

For the **posterior** study, 240 mandibular third molars were selected that were extracted for periodontal or orthodontic reasons. The freshly extracted teeth were immediately placed in 5.25% NaOCl for 5 minutes and then stored in 0.9% saline solution at room temperature until use, all within 2 months of extraction. During specimen preparation, the soft tissue covering the root surface was removed with hand scalers. The inclusion criteria were visual absence of caries, root cracks or resorptions, absence of previous endodontic treatment, posts or crown. Teeth with severe polymorphism of the coronal structures were excluded from the investigation.

About eighty percent of the specimens ranged 10.0 to 10.9 mm in size, when measured at the widest oro-vestibular dimension, and the rest were between 11.0 and 12.0 mm. The mesio-distal dimension of the samples was also measured, and this parameter allowed a maximum deviation of 10% from the determined mean.

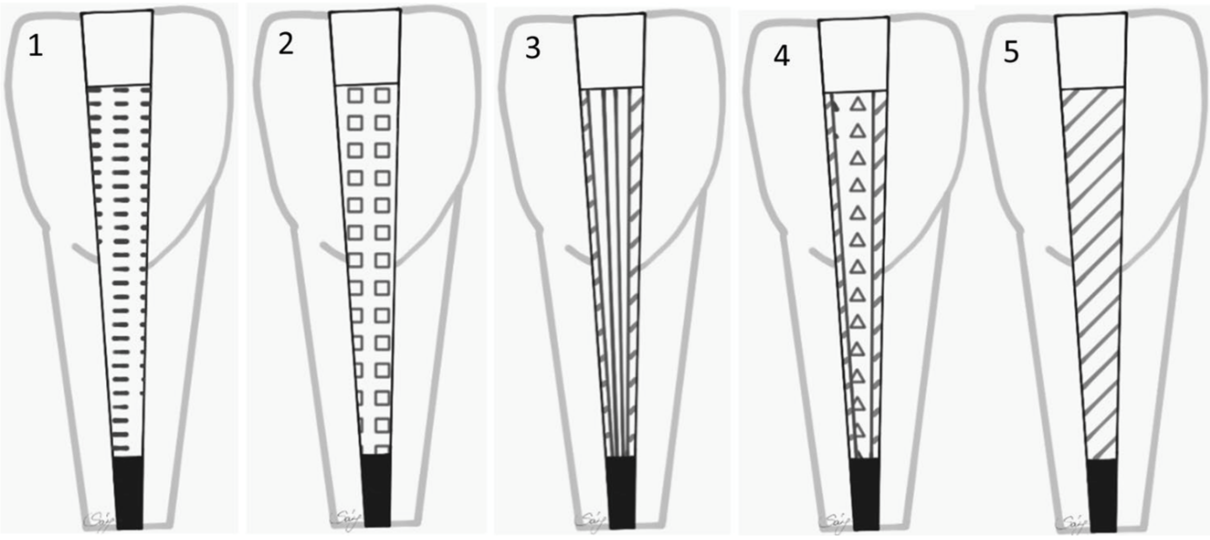
Specimen preparation and restorative procedures for anterior teeth

Teeth were randomly distributed among 6 study groups (n=30). One group was left intact to later serve as control (Group 6). The rest of the teeth (Group 1-5) were cut to obtain a length of 12 mm below the CEJ using a slow-speed, water-cooled diamond disc. Furthermore, after sectioning of the apical part, all teeth were examined under magnification for root fractures. The ones with a fracture, a visible crack or any sign of external resorption were excluded from the study and replaced with another tooth with adequate parameters.

Coronal access was made by using a round-end parallel diamond (881.31.014 FG – Brasseler USA Dental, Savannah, GA, USA) and an Endo Z bur (Dentsply Maillefer, Tulsa, OK, USA) in a high-speed handpiece. Next, the root canal was enlarged by Gates Glidden burs No. 1-6 with copious water cooling until an ISO size #140 could be passively extended through the apex. Each canal was then prepared with a GC Fiber Post drill size 1.6 (GC Europe, Leuven, Belgium) in order to simulate an immature tooth with thin walls. Each tooth was irrigated with 5 mL 5% NaOCl and 5 mL 17% ethylenediaminetetraacetic acid, followed by 5 mL of sterile water as the final rinse. A 4-mm apical plug of grey Pro-Root MTA (mineral trioxid aggregate) (Dentsply Tulsa Dental, Tulsa, OK, USA) was placed in each tooth with a MAP System (Dentsply Maillefer, Tulsa, OK, USA). The teeth were stored at 37°C and 100% humidity for 48 hours. After complete setting of the MTA was confirmed with an endodontic explorer and before restorative procedures, the radicular dentin was refreshened with a No. 4 Gates Glidden bur and flushed with chlorhexidine and saline. The enamel borders of the coronal cavity were acid-etched selectively with 37% phosphoric acid for 15 s and rinsed with water. The root canals were dried with paper points. For bonding, a dual-cure one-step self-etch adhesive system (G-Premio Bond and DCA, GC Europe, Leuven, Belgium) was used according to the manufacturer's instructions, using a microbrush-X disposable applicator (Pentron Clinical Technologies, LLC, USA). Excess adhesive was removed by suction drying (Evacuation Tip – Starryshine, Anaheim, CA, USA) within 0.5 cm from the occlusal cavity (without contact). Excess adhesive resin at the bottom of the canal was removed with a paper point. The adhesive was light cured for 60 s using an Optilux 501 quartztungsten-halogen light-curing unit (Kerr Corp., Orange, CA, USA). The average power density of the light source, measured with a digital radiometer (Jetlite light tester; J. Morita USA Inc. Irvine, CA, USA) prior to the bonding procedure, was 840 ± 26.8 mW/cm2.

The teeth in all groups were then treated as follows (Figure 1):

1. Figure: Schematic figure representing the anterior test groups (Group 1–5).



Group 1: The teeth were reconstructed with the Bioblock technique described by Fráter et al. [75] building a direct layered FRC post and core from SFRC. An increment of SFRC was packed to the apical portion of the post space using a microbrush-X disposable applicator (Pentron Clinical Technologies, LLC, USA). A light transmitting FRC post (1.4 mm GC Fiber Post, GC Europe, Leuven, Belgium) was inserted into the post space in order to aid the transmission of the light to the apically positioned layers. The 'light transmitting' post was withdrawn 0.5–1 mm from the surface of the uncured SFRC layer not to have direct contact with it. After each layer, 80 s of light curing through the fiber post was carried out. After incrementally filling the root canal to the level of the CEJ with repeating the previously described procedure, SFRC was layered in the coronal cavity until 2 mm below the margin of the occlusal cavity in a concave shape. Each coronally placed increment was light cured from the occlusal surface for 40 s. The last 2 mm thick occlusal layer was composite material (G-aenial Anterior JE, GC Europe, Leuven, Belgium) covering the SFRC.

Group 2: The teeth were reconstructed with SFRC flow (everX Flow, GC Europe, Leuven, Belgium) as described in Group 1.

Group 3: the teeth received a 1.5 mm diameter elastic FRC post (everStickPOST, GC Europe, Leuven, Belgium). Luting of the posts and the core build-up was performed with a dual-cure resin composite core material (Gradia Core, GC Europe, Leuven, Belgium). Gradia Core was applied using its own automix cartridge with an ‘elongation tip’ for direct root canal application. After the insertion of the post, the composite core material was polymerized from the top of the post with an Optilux 501 quartz-tungsten-halogen light-curing unit for 60 s from each side (a total of 240 s/tooth). The last 2 mm thick occlusal layer was composite material as in Group 1.

Group 4: the teeth received a 1.6 mm diameter conventional FRC post (GC Fiber Post). The conventional translucent FRC posts were tried in and cut to a length of 2 mm below the level of the occlusal cavity margins with a water-cooled diamond disc (Isomet 2000; Buehler Ltd., Lake Bluff, IL, USA) and cleaned with alcohol after try in. The posts received silanization of the surface (Ceramic Primer II, GC Europe, Leuven, Belgium) following the manufacturer’s recommendations. After silanization, the post surface was bonded with the same bonding agent used for the cavity. Luting of the posts and the core build-up was performed with a dual-cure resin composite core material (Gradia Core) as in Group 3. The last 2 mm thick occlusal layer was composite material as in Group 1.

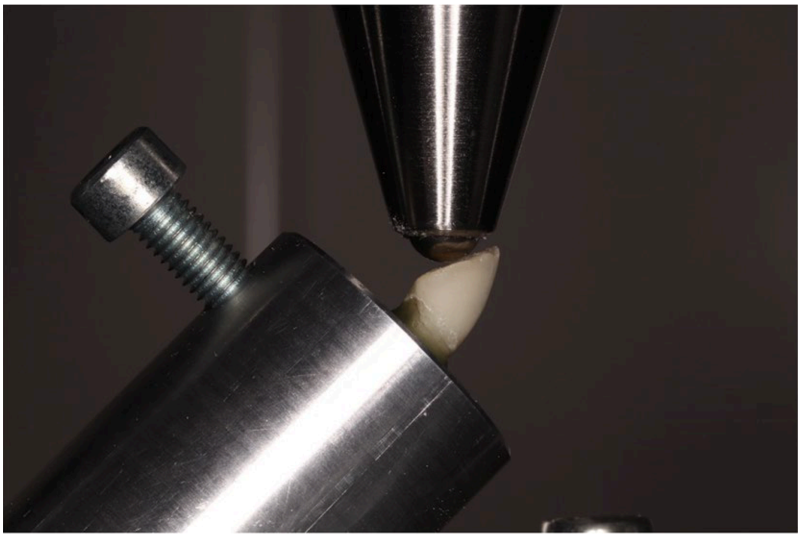
Group 5: The teeth were reconstructed with a dual-cure resin composite core material (Gradia Core) without any FRC material. Gradia Core was applied using its own automix cartridge with an ‘elongation tip’ for direct root canal application. Both the root canal and the coronal cavity was filled up with the core material. The light curing was the same as in Group 3. The last 2 mm thick occlusal layer was composite material as in Group 1.

Ultimately for all restored teeth, glycerine gel (DeOx Gel, Ultradent Products Inc., Orange, CA, USA) was applied and final polymerization was carried out from each side for 40 s. The restorations were finished with a fine granular diamond burr (FG 7406-018, Jet Diamonds, USA and FG 249-F012, Horico, Berlin, Germany) and aluminum oxide polishers (OneGloss PS Midi, Shofu Dental GmbH, Ratingen, Germany).
After the restorative procedures, mechanical testing was carried out on 25 anterior teeth from each group (including control group) (n= 150) and 5 anterior teeth from each restored group (n=25) underwent sectioning, microleakage and microhardness testing.

Embedding and accelerated fatigue testing of anterior teeth

The restored specimens were stored in physiological saline solution (Isotonic Saline Solution 0.9%; B. Braun, Melsungen, Germany) in an incubator (mco-18aic; Sanyo, Moriguchi, Japan) at 37°C. To simulate the periodontal ligaments, the root surface of each tooth was coated with a layer of liquid latex separating material (Rubber-Sep, Kerr, Orange, CA) prior to embedding. All specimens were embedded in methacrylate resin (Technovit 4004, Heraeus-Kulzer, Hanau, Germany) at 2 mm from the CEJ to simulate the bone level.
For mechanical testing, the restored specimens were submitted to a modified accelerated fatigue-testing protocol by a hydraulic testing machine (ElektroPlus E3000, Norwood, MA, USA) at an angle of 135 degrees to the long axis of each tooth. Cyclic isometric loading was applied on the palatal surface of the coronal part of the tooth using a round-shaped metallic tip (Figure 2). A cyclic load was applied at a frequency of 5 Hz, starting with gradually increasing static loading till 100 N in 5 seconds, followed by cyclic loading in stages of 100 N, 200 N, 300 N, 400 N, 500 N and 600 N at 5,000 cycles each. Specimens were loaded until fracture occurred or until the total of 30 000 cycles were carried out, which was the whole testing procedure. For the survival analyses, the number of cycles at which the specimen failed were recorded.

2. Figure: Embedded specimen loaded at 135 degree on the palatal surface.

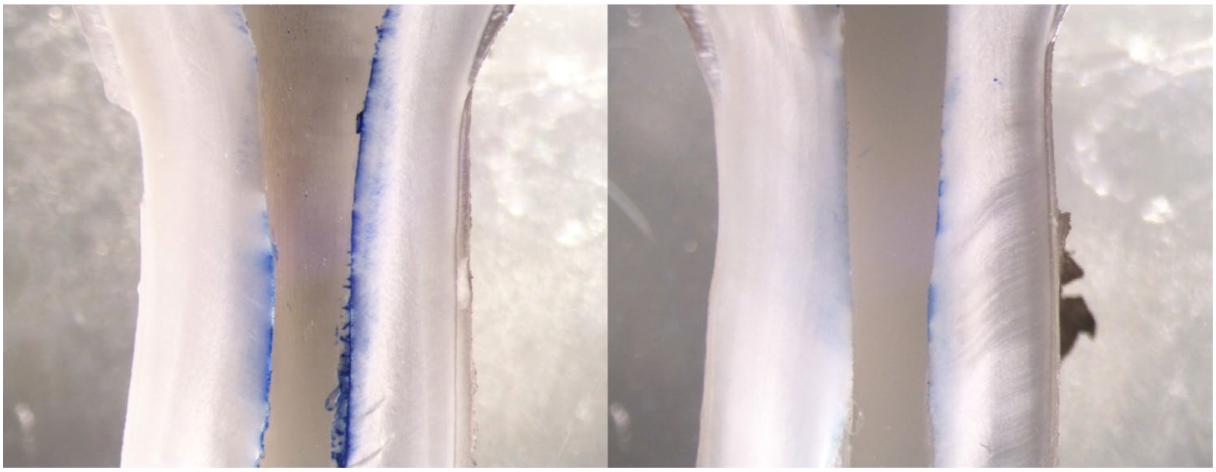


The failed specimens were visually examined to identify the type and location of the failure, as well as the direction of the failure. According to Scotti and co-workers and with the agreement of two other examiners, the tested teeth were distributed among two groups: restorable and non-restorable [89]. A restorable fracture is above the CEJ, meaning that in case of fracture, the tooth can be restored, while a non-restorable fracture extends below the CEJ and the tooth is likely to be extracted [89].

Microleakage Test

Five groups, each consisting of 5 endodontically treated and restored anterior teeth, were investigated in the microleakage test. The teeth were restored in the same way as mentioned earlier (Group 1-5). Teeth were sectioned sagitally in the mid-mesio-distal plane using a ceramic cutting disc, operating at a speed of 100 rpm (Struers, Glasgow, Scotland) under water cooling. In each group, one of the sectioned restorations that contained the post, was further grinded and polished using #4000-grit silicon carbide papers at 300 rpm under water cooling with an automatic grinding machine (Rotopol-1; Struers, Copenhagen, Denmark). Thereafter the sectioned teeth were painted with a permanent marker and polished gently for a few seconds. The dye penetration along the post/core margins of each section was evaluated independently using a stereo-microscope (Heerbrugg M3Z, Heerbrugg, Switzerland) at a magnification of 6.5x. The extent of dye penetration was recorded in mms and was later calculated as a percentage of the total margin length (Figure 3).

3. Figure: Pictures of sectioned specimens (Groups 4 and 5) showing microgaps at resin composite-root canal interface.



Microhardness test

Microhardness of the luting composite and the SFRC inside the canal was measured using a Struers Duramin hardness microscope (Struers, Copenhagen, Denmark) with a 40 objective lens and a load of 1.96 N applied for 10 s. Each sectioned restoration was subjected to 5 indentations on the top and the bottom of the canal. The diagonal length impressions were measured, and Vickers values were converted into microhardness values by the machine. Microhardness was calculated using the following equation:

$$H = \frac{1854.4 \times P}{d^2}$$

where H is Vickers hardness in kg/mm^2, P is the load in grams and d is the length of the diagonals in µms.

Microscopic analysis

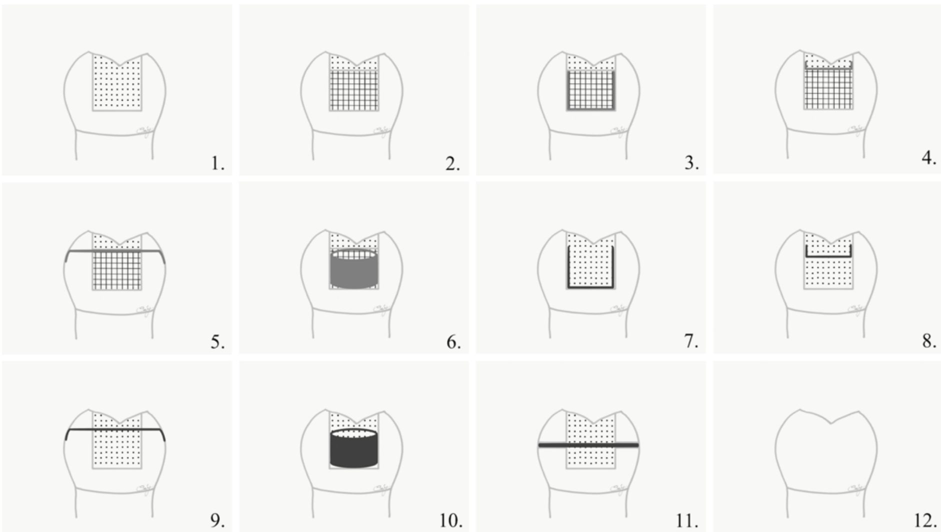
Scanning electron microscopy (SEM, JSM 5500, Jeol Ltd., Tokyo, Japan) provided the characterization of the microstructure and microleakage examination of the investigated restorations. The sectioned teeth were coated with gold sputter prior to the SEM examination.

Specimen preparation and restorative procedures for molar teeth

The teeth were randomly distributed over 12 study groups (n=20). One group was left intact to later serve as control (Group 12). The rest of the teeth received a standardized MOD cavity preparation with the remaining walls being 2.5 mms thick and the depth of the cavity being 5 mms deep, prepared by the same trained operator as described by Forster et al. [74]. The preparation was performed with a round end parallel diamond bur (881.31.014 FG - Brasseler USA Dental) initially positioned at the midline of the occlusal surface of the teeth. This position was determined by dividing the distance between the buccal and lingual cusp tips. The thickness of the opposing walls at the cavity base were continuously checked during the preparation with a digital caliper (Mitutoyo Corp., Kawasaki, Japan) and adjusted to have a uniform 2.5 mm thickness at the base of the cavity. The cavity walls were prepared parallel to the long axis of the tooth. The depth of the cavity was measured at 5 mms and evaluated with a 15 UNC periodontal probe (Hu-Friedy Mfg. Co., Chicago, USA), measured from the corresponding cusp tip by touching the cavity wall with the full length of the instrument. The cavity was one continuous cavity with the pulpal box having exactly the same dimensions as the occlusal one. The cavosurface margins were prepared perpendicular to the tooth surface at the end of the preparation. Only in Group 11 were both the buccal and lingual walls pierced, creating an artificial whole with the width of approx. 2-3 mms, positioned above the equator of the tooth with a diamond micropreparation bur (MP 53, TwoStriper, Airbrasive Tehcnology inc. USA). After the preparation, all cavities were rinsed with water and air-dried with an air/water syringe. All samples received the same adhesive treatment. After application of a Tofflemire (1101C 0.035, KerrHawe, Bioggio, Switzerland) matrix band, the enamel was acid-etched selectively with

37% phosphoric acid for 15 seconds, rinsed with water and air-dried. The cavity was adhesive-treated with G-Premio Bond (GC Europe) according to the manufacturer's instructions. The adhesive layer was light-cured for 40 s with an Optilux 501 halogen light (Kerr), operating in standard mode at a light intensity of 740+/- 36 $mWcm^2$. In all groups, an approximately 0.5 mm thick flow composite layer (G-aenial Flo, GC Europe, Leuven, Belgium) was applied on the floor of the cavity. This layer was light-cured for 40 s. After applying the flowable, the interproximal walls were built up with composite (G-aenial Posterior PJ-E, GC Europe, Leuven, Belgium) using the centripetal technique, thereby transforming the MOD cavity into a Class I cavity. From this point on, the cavities were distributed among 11 groups according to the different direct restorative techniques. The cavities were restored as follows (Figure 4):

4. Figure: Schematic figure representing the molar test groups (Group 1-12).



Group 1: The cavities were restored with a microhybrid composite restorative material (G-aenial Posterior PJ-E), applied with an oblique incremental technique, placed in consecutive 2 mm thick increments. Each layer was light cured from the occlusal surface for 40 seconds. Glycerine gel (DeOx Gel) was applied and final polymerization was performed from each side for 40 seconds with Optilux 501. The finishing and polishing were the same in all groups, in more detail a fine granular diamond burr (FG 7406-018, Jet Diamonds, USA and FG 249-F012, Horico, Germany) and aluminum oxide polishers (OneGloss PS Midi).

Group 2: The cavities were restored with an SFRC material (everX Posterior) applied in a bulk-fill technique. The material was placed in a single increment according to the anatomy of the dentin, leaving 1.5-2 mms occlusally for the final composite layers as prescribed by the manufacturer. This increment was light cured from the occlusal surface for 40 seconds. The last occlusal layer was composite material (G-aenial Posterior PJ-E) covering the SFRC. Glycerine gel (DeOx Gel) was applied and final polymerization from each side for 40 s with Optilux 501 was performed.

Group 3: A piece of 3 mm wide pre-impregnated glass fiber net (everStickNET) with a size approx. the same as the remaining cavity was cut and placed on “the bottom” of the cavity in a bucco-lingual direction. The net was placed in a way that it would not reach the margins of the cavity, leaving 1.5-2 mm space for the future occlusal composite layer. In all groups where the net was used, it was adapted to the walls with a periodontal probe (Hu-Friedy) slightly wetted in resin (Stick RESIN, GC Europe, Leuven, Belgium) and handled according to manufacturer’s instructions. After curing for 40 s, the cavity was restored with SFRC and a final layer of occlusal composite as described in Group 2.

Group 4: First, the cavities were restored with SFRC as described in Group 2. When there was only approx. 1.5-2 mm space remaining occlusally in the cavity, a piece of 3 mm wide pre-impregnated glass fiber net (everStickNET) was placed on the cavity walls in a bucco-lingual direction. The net was placed so that it would not reach the margins of the cavity. After curing for 40 s, the cavity was restored with a final layer of occlusal composite as in Group 2.

Group 5: The cavities were restored with SFRC and a final layer of occlusal composite as in Group 2. After finishing the restoration, a 4 mm wide and 1.5 mm deep groove was prepared on the occlusal surface of the restoration between the cusp tips, from a buccal to lingual direction, with a high-speed bur under water cooling. Both end of each groove was on the coronal one-third of the buccal and lingual walls of the teeth. After selective enamel etching in the mentioned area, the groove was rinsed, dried and adhesively treated (G-Premio Bond). A piece of pre-impregnated glass fiber net (everStickNET), matching the size of the prepared groove, was cut and placed into the groove. After curing for 40 s, the cavity was restored with a final layer of occlusal composite as in Group 2.

Group 6: 1 piece of 3 mm wide pre-impregnated glass fiber net (everStickNET) was placed in the cavity, applied circumferentially to the walls. The net was placed so that it would cover the axial walls but not reach the margins of the cavity. After curing for 40 s, the cavity was restored with SFRC and a final layer of occlusal composite as in Group 2.

Group 7: 1 piece of 3 mm wide Leno Weave Ultra High Modulus (LWUHM) polyethylene ribbon fiber (Ribbond-Ultra THM; Ribbond Inc., Seattle WA, USA) was placed into the cavity covering the cavity walls in a bucco-lingual direction forming a fiber layer with Ribbond just as in Group 3, only there with the glass fiber net. In all groups where polyethylene fibers were used, the fibers were first saturated with adhesive resin (StickRESIN), the excess resin was removed with a hand instrument and then placed into the bed of un-cured flowable composite (G-aenial Universal Flo). The fiber was placed in so that it would not reach the margins of the cavity. After curing for 40 s, the cavity was restored with microhybrid composite as in Group 1.

Group 8: The cavities were restored with a microhybrid composite applied in an oblique incremental technique. The material was placed in consecutive 2 mm thick increments. Each increment was light cured from the occlusal surface for 40 seconds. When there was only approx. 1.5-2 mm space remaining of the cavity occlusally, 1 piece of 3 mm wide LWUHM polyethylene ribbon fiber (Ribbond-Ultra THM) was cut and placed in the remaining cavity in a bucco-lingual direction, forming a fiber layer with Ribbond just as in Group 4 with the glass fiber net. After handling of the fibers and curing for 40s, the cavity was restored with a final layer of occlusal composite as in Group 1.

Group 9: the cavity was restored with microhybrid composite as in Group 1. After finishing the restoration, a 4 mm wide and 1 mm deep groove was prepared on the occlusal surface of the restoration between the cusp tips, from a buccal to lingual direction, with a high-speed bur under water cooling. The end of each groove was on the coronal one-third of the buccal and lingual walls of the teeth. After selective enamel etching in the mentioned area, the groove was rinsed, dried and adhesively treated (G-Premio Bond). A piece of LWUHM polyethylene ribbon fiber (Ribbond-Ultra THM) was placed into the groove. After handling of the fibers and curing for 40 s, the cavity was restored with a final layer of occlusal composite.

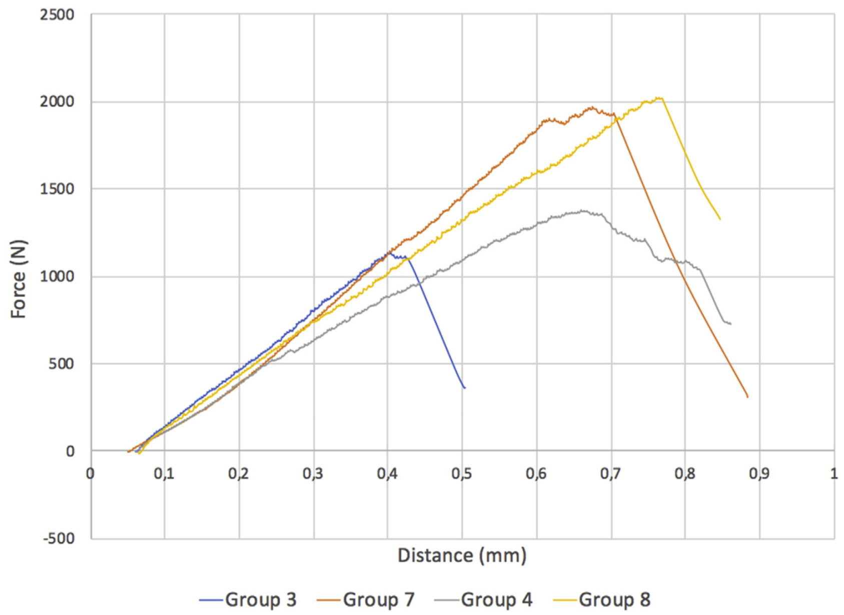
Group 10: A piece of LWUHM polyethylene ribbon fiber (Ribbond THM) was cut and placed on the cavity walls circumferentially. The fiber was handled and adapted into flowable composite as in Group 7. After curing for 40 s, the cavity was restored with microhybrid composite as in Group 1.

Group 11: 1 piece of 1 mm wide LWUHM polyethylene ribbon fiber (Ribbond Ultra Orthodontic; Ribbond Inc., Seattle WA, USA) was placed through the previously performed holes on the buccal and lingual walls. This ribbon was placed into the prepared grooves on the external coronal surfaces, connecting the opposing walls like a tightrope. First the polyethylene fibers were fixed in one groove, light cured and covered with composite, and subsequently the rest of the fibers on the opposing side were tightly positioned with a tweezer and fixed to the opposing groove by light curing and composite coverage. This produced a “transcoronal splinting” inside the cavity. After curing for 40s, the cavity was restored with microhybrid composite as in Group 1.

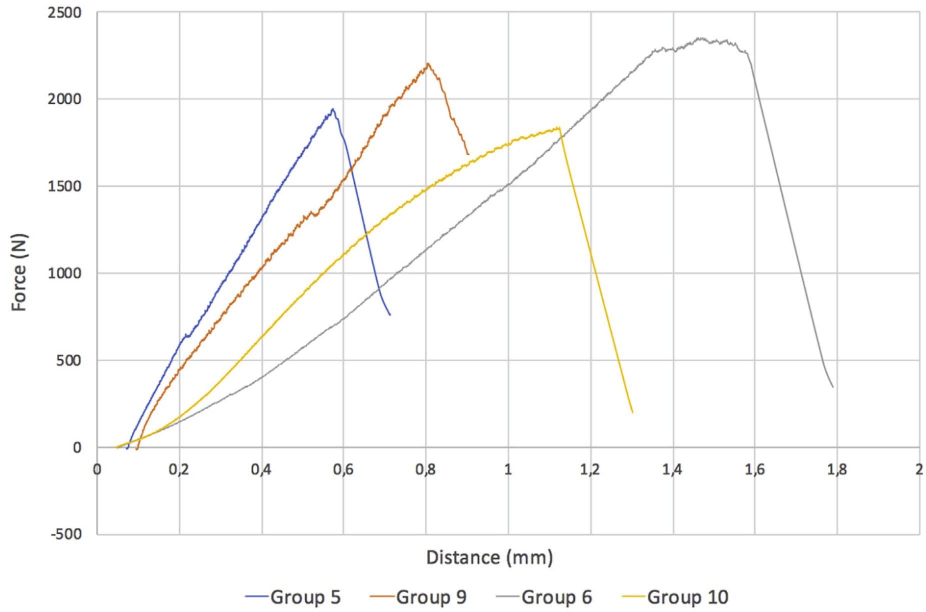
Embedding and mechanical testing of molar teeth

The restored specimens were stored in physiological saline solution and subsequently embedded as described previously in the anterior study. Immediately after embedding, all specimens were subjected to a fracture resistance test. Teeth were quasi-statically loaded with a crosshead speed of 2 mm/minute, parallel to the long axis of the tooth in a universal testing machine (5848 MicroTester1, Instron, Norwood, MA, USA), until they fractured. A cylindrical steel bar, which was 6 mm in diameter and 10 mm long was used [90, 91]. The bar was positioned at the center of the occlusal surface of the crown between the buccal and oral cusps. A force vs. distance curve was dynamically plotted for each tooth. Failure load — defined as the load at which the tooth-restoration complex exhibited the first fracture, resulting in a peak formation on the force versus distance curve — was recorded in Newtons (N). In each case the specific failure load was determined when the force versus distance curve showed an abrupt change in load, indicating a sudden decrease in the specimen’s resistance to compressive loading (Figure 5,6)

5. Figure: Force versus distance curves of specimens representing each study groups. Peaks indicate the amount of maximal failure load.



6. Figure: Force versus distance curves of specimens representing each study groups. Peaks indicate the amount of maximal failure load.



After recording failure load, each specimen was visually examined for the type and location of failure (restorable or non-restorable fracture), as described above in the anterior study.

Statistical analysis

Statistical analysis was conducted in SPSS 23.0 (SPSS Inc., Chicago, IL).
In the anterior study the number of survived cycles was analyzed descriptively for each group and with the Kaplan-Meier method across the groups (with the Breslow test for the pairwise analyses). The frequency of restorable and non-restorable fractures was calculated for each group.

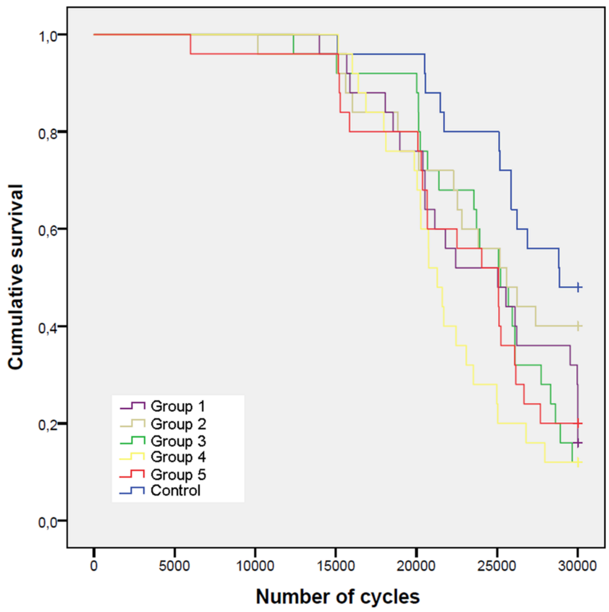
In the molar study for the comparisons between the groups, ANOVA with Tukey's HSD post-hoc test was used.

The general limit of significance was set at $\alpha=0.05$ in both studies.

Results

The Kaplan–Meier survival curves of the **anterior** samples are displayed in Figure 7. Table 1 shows the p values for group-wise comparisons. In the anterior study the survival rate of Group 2 did not differ significantly from the intact teeth (control group). The rest of the anterior groups had significantly lower survival rates compared to the anterior control group. Thus, the 1st null hypothesis was rejected. All restored anterior groups showed exclusively irreparable fractures, whereas the control group had some that were reparable, but most fractures were irreparable in this group as well (Table 2). Therefore the 2nd null hypothesis was accepted.

7. Figure: Fatigue resistance survival curves (Kaplan–Meier survival estimator) for all six groups.



1. Table: p values of pairwise log-rank post hoc comparisons (Kaplan–Meier survival estimator followed by log-rank test for cycles until failure or the end of the fatigue loading among all 6 groups)

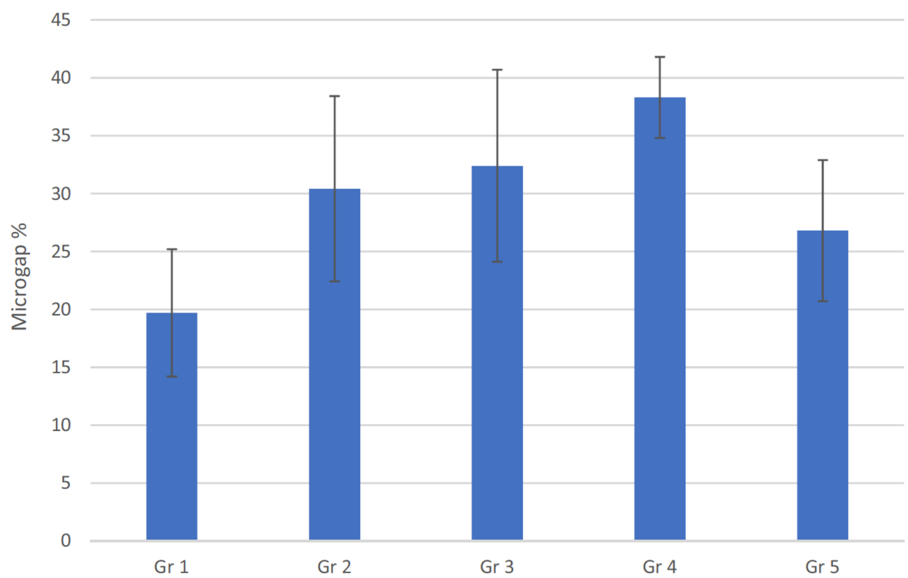
GROUPS	Control		Group 1		Group 2		Group 3		Group 4		Group 5	
	Chi square	Sig.	Chi square	Sig.	Chi square	Sig.	Chi square	Sig.	Chi square	Sig.	Chi square	Sig.
Control (intact teeth)	-	-	5.551	0.018	1.722	0.189	6.208	0.013	13.801	0.000	7.083	0.008
Group 1	5.551	0.018	-	-	0.793	0.373	0.000	1.000	1.434	0.231	0.143	0.705
Group 2	1.722	0.189	0.793	0.373	-	-	0.355	0.551	3.401	0.065	1.003	0.316
Group 3	6.208	0.013	0.000	1.000	0.355	0.551	-	-	3.467	0.063	0.254	0.614
Group 4	13.801	0.000	1.434	0.231	3.401	0.065	3.467	0.065	-	-	1.027	0.311
Group 5	7.083	0.008	0.143	0.705	1.003	0.316	0.254	0.614	1.027	0.311	-	-

2. Table: The distribution of fracture pattern among the study groups (n = 25)

FRACTURE PATTER	Group 1	Group 2	Group 3	Group 4	Group 5	Intact teeth
Restorable	0	0	0	0	0	2
Non-restorable	18	15	22	22	20	11
Fractured teeth	18	15	22	22	20	13
Non-fractured teeth	7	10	3	3	5	12

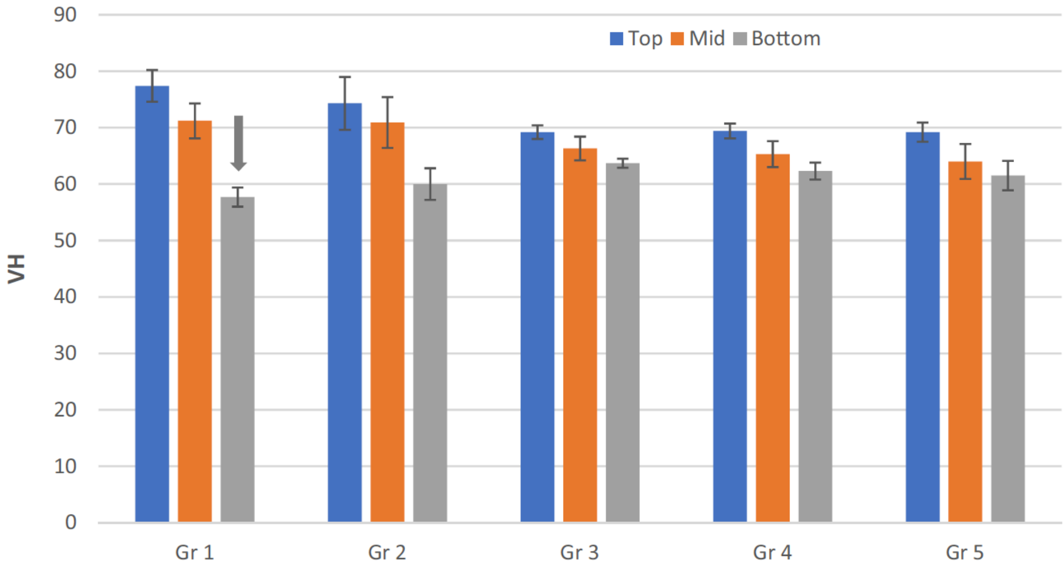
The mean values and standard deviations of microgap percentages at the post/core-root canal interface of the five restored anterior groups are presented in Figure 8. According to our findings, the Bioblock technique (Group 1) had low percentage of microgaps (19.7%) compared to the other groups, whereas Group 4 exhibited a remarkably high number of microgaps (38.3%) at the examined interphase in the root canal.

8. Figure: Mean percentage of microgaps observed in the anterior restored groups



The surface microhardness (Vickers hardness) of the luting composite and SFRCs decreased gradually within a limited range with increasing depth (Figure 9.) The data showed no difference in Vickers hardness values between the tested dual-core luting composite and SFRCs at the top and middle parts of the canal. However, at the apical part, packable SFRC (Group 1) presented the most drastic decrease along with Vickers hardness values.

9. Figure: Microhardness (Vickers hardness) mean values for resin composites at the top (coronal), middle and bottom (apical) part of the root canal. The arrow above Group 1's third/bottom column indicates that the Vickers hardness of this group dropped below 80% of the coronal part's value. Vertical lines represent standard deviation (SD)



Regarding the **molar** study, Table 3. summarizes the fracture thresholds for the different study groups. Teeth with transcoronal splinting (Group 11) yielded the highest fracture resistance among the restored molar groups, and interestingly, this was slightly even higher than that of the molar control group (intact teeth). Groups 1, 3 and 4 showed significantly lower fracture resistance values compared to intact molar teeth, <u>thus the 3rd null hypothesis was rejected.</u> The results of the post-hoc pairwise comparisons (Tukey's HSD) are given in Table 4. In terms of fracture pattern (Table 5.), the type and position of fibers within the restoration influenced the ratio of favorable and unfavorable fractures. Only SFRC (Group 2) was characterized by the highest percentage of favorable (i.e., reparable) fractures, while composite alone (Group 1) and transcoronal splinting (Group 11) yielded the lowest ratio. <u>Therefore, the 4th null hypothesis regarding fracture pattern was also rejected.</u>

3. Table: Descriptive statistics of the results by group. Group 1: composite; Group 2: SFRC; Group 3: B-L net at the bottom; Group 4: B-L net at the top; Group 5: net occlusal splinting; Group 6: net circumferential; Group 7: Ribbond B-L at the bottom; Group 8 Ribbond B-L at the top; Group 9: Ribbond occlusal splinting; Group 10: Ribbond circumferential; Group 11: Ribbond transcoronal splinting; Group 12: control

GROUPS	n	Mean (Newton)	SD
Group 1	20	1629.45	503.11
Group 2	20	1746.25	467.50
Group 3	20	1122.20	440.04
Group 4	20	1408.65	314.59
Group 5	20	1925.60	792.69
Group 6	20	2067.30	535.80
Group 7	20	1834.40	578.56
Group 8	20	2022.05	771.41
Group 9	20	2129.25	629.75
Group 10	20	1906.95	538.09
Group 11	20	2484.80	682.90
Group1 12	20	2266.30	601.14

4. Table: Significance matrix from the post-hoc pairwise comparisons (Tukey's HSD). The conventions are the same as in Table 1. Empty cells indicate lack of significance.

GROUPS	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Group 10	Group 11	Group 12
Group 1	-										0.000	0.033
Group 2		-	0.041								0.005	
Group 3		0.041	-		0.001	0.000	0.009	0.000	0.000	0.002	0.000	0.000
Group 4				-		0.002		0.049	0.007		0.000	0.000
Group 5			0.001		-							
Group 6			0.000	0.023		-						
Group 7			0.009				-				0.026	
Group 8			0.000	0.049				-				
Group 9			0.000	0.007					-			
Group 10			0.002							-		
Group 11	0.000	0.005	0.000	0.000			0.026				-	
Group 12	0.033		0.000	0.000								-

5. Table: Fracture pattern by groups. Number of observation and group percentages. The conventions are the same as in Table 1.

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Group 10	Group 11	Group 12
Reparable	4 (20%)	16 (80%)	8 (40%)	14 (70%)	13 (65%)	14 (70%)	8 (40%)	10 (50%)	10 (50%)	12 (60%)	4 (20%)	18 (90%)
Irreparable	16 (80%)	4 (20%)	12 (60%)	6 (30%)	7 (30%)	6 (30%)	12 (60%)	10 (50%)	10 (50%)	8 (40%)	16 (80%)	2 (10%)

Discussion

One of the main goals in restoring both vital and ET teeth is recovering lost resistance to masticatory loads, consequently reinforcing the tooth-restoration complex [92].

Traumatic dental injuries to developing teeth are common in patients between the ages of 8 and 12 years [93] and mostly affect the maxillary central incisors [94]. These injuries often lead to pulpal necrosis with a subsequent cessation of root formation [95]. The result is the formation of an immature tooth with divergent, thin dentinal walls and an open apex. Subsequently, these teeth are highly susceptible to fracture, especially in the cervical area [96]. As retaining these teeth during the craniofacial growth of the patients is critical, the concept of intraradicular reinforcement of immature teeth after one-shot apexification has been receiving increased attention nowadays [97]. In our anterior study, both long unidirectional (in the form of an FRC post) and short fiber-reinforced composite materials were used with the aim of reinforcing immature teeth.

In the **anterior** study, cyclic loading was used instead of static load-to-fracture testing. Cycling loading corresponds better to the clinical situation, as it generates repetitive forces similar to those of normal chewing, and such fatigue causes root fractures more often than static forces [98]. The accelerated fatigue testing method used was based on the protocol of Magne et al. [99, 100] This method represents an attempt to strike a balance between the load-to-fracture and the more sophisticated and time-consuming fatigue tests [101]. Similar to other in vitro mechanical studies that target anterior teeth, a 135-degree loading angle was used to simulate normal masticatory loads, applied to the palatal area of an upper anterior tooth [97, 102, 103]. While Group 2 did not differ in survival from the intact teeth (control group), all other restored groups showed significantly lower survival rates. This could be due to the previously mentioned unique properties, i.e., extremely high amount of fibers, of the flowable SFRC (please see above).

In the Bioblock technique, packable SFRC is directly and closely adapted to the root canal wall, eliminating the disadvantages of luting cements or the biomechanically incorrect positioning of the FRC posts, thus potentially diminishing all the damaging tensile stresses produced when the restoration is loaded [75]. Although the survival of the Bioblock technique (Group 1) did not differ from the flowable SFRC group (Group 2), it showed a significantly lower survival rate than intact teeth.

In our previous study on restoring ET premolars with MOD cavities, the packable SFRC inside the root canal produced significantly higher fracture resistance values compared to teeth restored with FRC posts [75]. This apparently contradicts with the findings of Forster et al., where packable SFRC inside the root canal did not significantly differ in fracture resistance from the teeth restored with a conventional FRC post [104]. It must be noted however, that the latter study examined ET premolars exclusively with Class I cavities and used a static load-to-fracture setup. In the present anterior study, we found no difference between the groups restored with different types of posts (conventional or individually made) in terms of survival. This seems to complement our previous findings regarding fracture resistance (a proxy of survival) [105]. The reinforcing effect of FRC posts in immature teeth is a matter of ongoing debate. According to Jamshidi et al. [106], and Linsuwanont et al. [97] FRC posts cannot reinforce immature teeth, as the fracture resistance after post insertion is significantly lower compared to intact teeth. In contrast, in the study of Schmoldt et al., immature teeth restored with FRC posts showed higher fracture resistance compared to intact teeth [102]. It must be noted that all these studies used static load-to-fracture testing.

In our study, FRC posts failed to reinforce immature anterior teeth. As shown by Ambica et al., cyclic loading reduces the fracture strength of ET teeth restored with FRC posts [107]. Theoretically, long unidirectional fibers in the form of posts should be more suitable for the anterior region, as the forces in this region act nearly perpendicular to the tooth and therefore the fibers. Still, we found that these unidirectional reinforcements could not efficiently strengthen or increase the survival of immature teeth. Moreover, they did not exceed the dual-cure core build-up material applied by itself either (Group 5). The reason behind the inferior performance of FRC posts in this situation, compared to intact teeth, is presumably their inadequate fit in the critical cervical part of the mechanically already compromised teeth. Vallittu concluded that the success of restorative procedures involving post insertion could be determined by the amount and adaptation of fibers in the critical cervical part of the tooth [108]. If the post does not fit well, especially at the cervical level, the resin cement layer can be too thick and bubbles are likely to form in it, which can lead to de-bonding [109, 110]. Therefore, the amount of fibers should be maximized and the amount of luting cement should be minimized in the critical cervical region [108]. This seems to be the case when looking at our current and previous results by Fráter et al. [75] on microgap formation with teeth restored with conventional FRC posts, as in our study Group 4 produced many microgaps at the interface. Although the posts used in our groups (Groups 3 and 4) were large, they failed to reinforce the weakened immature teeth.

Looking at the sectioned samples, survival itself does not seem to directly correlate with marginal microgap formation at the interface inside the canal. The packable version of SFRC (Group 1) had remarkably good adaptation to the canal walls among all tested materials, which was in accordance with the findings of Fráter et al. [75]. This finding is also in accordance with the concept of the monoblock theory. This states that it is always beneficial to reduce the number of interphases in a restoration-tooth complex, as they do not only concentrate but also increase the amount of stress within the restored unit [111]. In the Bioblock technique, SFRC is directly adapted to the root canal wall, enabling the clinician to fill and restore any root canal, even with an irregular cross-section that would otherwise be deemed not ideal for FRC post insertion. With the Bioblock technique, the number of fibers can also be maximized in the critical cervical area of the tooth, which appears to be crucial regarding future stress accumulation [108]. While the adaptation of the packable SFRC to the cavity/root canal walls was ideal, gaps and voids were frequently found within the material itself. This phenomenon has also been noticed by clinicians when using packable SFRC in a bulk manner. Our opinion is that these bubbles could partly be a sign of internal stress relief, as shrinkage is inevitable during the setting of the material. In case this shrinkage does not occur at the interface, it might cause internal voids inside the bulk material itself. In addition, some of these bubbles and microgaps could be due to poor compression of the material inside the narrow space, or entrapment of air when applying the material into the canal.

The microhardness values show that even the SFRC materials could be properly cured, nearly reaching the microhardness levels of dual-cure materials. This is in accordance with previous findings, showing that SFRC can be sufficiently light cured inside the canal [75]. As shown by Garoushi et al. [46] and Lempel et al. [48, 49], SFRC can be light-cured to a depth of 4–5 mms. This is caused by both the translucency of the material and the fact that the randomly oriented fibers within may conduct and scatter the light to deeper layers [112]. Interestingly, in this study we found the microhardness values to be higher than that in a previous study with premolar teeth [75]. This might be traced back to the wider root canals in immature teeth, which may make it possible for more light to access the more apically positioned layers in the canal. Furthermore, due to the wider root canal, a wider FRC post could be used for light transmission during the Bioblock technique (Groups 1 and 2), which could theoretically transfer a greater amount of energy apically, compared to a smaller sized FRC post.

Bovine teeth were used for this anterior study, as extracted human anterior teeth are not readily available and their anatomical variability is quite high. Bovine teeth are commonly used when anterior restorations need to be modelled in higher numbers [99, 100], as bovine dentin is considered to be similar to human dentin regarding composition and geometric root configuration as well [113, 114]. Nonetheless, we still consider this a shortcoming in our study.

When redirecting our attention to the **posterior** region, we may find that molar teeth with significant damage or carious lesions are routinely treated by extensive MOD fillings thanks to recent advances in adhesive technology and composite materials [115]. In our posterior study, deep MOD cavities were restored with various direct restorative techniques. The dimensions of these MOD cavities resemble a large direct amalgam filling replacement, which is also becoming common in the daily clinical routine [116]. However, as previously stated, polymerization shrinkage is a serious problem for large direct composite restorations [117, 118], resulting in cuspal strains with subsequent stress or disruption of the bond, in microleakage and recurrent caries, or even in enamel cracking [117]. The other fundamental problem with composite materials is their inadequate fracture toughness, which was shown to be significantly lower than that of dentin – the tissue it is meant to (mostly) replace [119]. As modern composite resin materials are rigid, they do not lack strength, but toughness [119]. The matter is particularly well seen in extensive direct restorations, as the volume of the material naturally increases in these cases [120]. As a result of the above-mentioned disadvantages, direct composite fillings might not be the best solution in extensive MOD cavities in posterior teeth. In our study, teeth restored with layered composite fillings (Group 1) showed significantly lower fracture resistance than intact teeth (Group 12) (p=0.033). This is in accordance with the results of Forster et al., showing that vital molar teeth with large cavities cannot be successfully reinforced with direct composite fillings [74]. The same was shown by Papadopoulos et al., who compared the fracture resistance of natural intact teeth with teeth with MOD cavities, restored with a bulk-fill composite [121]. Scholtanus et al. found that premolar teeth with MOD cavities restored with direct composite fillings were significantly weaker than intact teeth, though in their study, one cusp was also replaced with composite material [122]. According to Forster et al. the depth of the cavity is of critical importance when a direct restorative technique is chosen in MOD cavities [74]. Not only is the cantilever effect greater in deeper cavities, but also the volume of the restorative material, which thereby empathizes the shortcomings of conventional composite materials. In our study, this problem is reflected both in fracture resistance values and the fracture pattern of teeth restored with composite fillings. Regarding fracture pattern, Group 1 was characterised by predominantly non-restorable fractures. Stress-absorption and crack-arresting ability is attributed to the DEJ and to the dentin adjacent to this interphase [123]. The more structurally compromised the tooth is, the lower the proportion of DEJ and sound dentin, and the higher the chance for catastrophic failure in the restoration-tooth continuum. A material with high fracture toughness can better resist crack initiation and propagation, thus would be more ideal to replace the missing DEJ and/or dentin core. SFRC is intended to be used mainly in the posterior region and/or in structurally compromised teeth as a dentin replacing material [46]. The well documented toughening ability of SFRC over conventional composites is due to multiple factors that have been well described in the previous sections. In our posterior study, teeth restored with SFRC (Group 2) did not show statistically significant difference from intact teeth (Group 12) in terms of fracture resistance. Also, the fracture pattern changed to predominantly favorable fractures, compared to the composite group (Group 1) where it was mostly non-favorable. In fact, the SFRC group produced the highest number of favorable fractures among all restored posterior groups. This is in accordance with Fráter et al., where the SFRC was able to shift the fracture pattern to predominantly favorable even in shallower MOD cavities [73]. Several studies have shown that the SFRC substructure supports the composite restoration and serves as a crack-prevention layer [60, 63, 64], The thickness of the SFRC core is of utmost importance, as it influences the failure mode and the crack-arresting mechanism [65].

In this study, SFRC was applied in a biomimetic manner, replacing the missing dentin up until the level of the lost DEJ, in order to substitute both tissues simultaneously, following Monaco et al., who suggested that the highest fracture resistance could be achieved this way [124].

Deep MOD cavities are susceptible to fracture [125], which is mainly caused by the increased cavity dimensions and the loss of marginal ridges [71], leading to increased cuspal flexure and overall weakening of the tooth [117]. In order to stabilize the remaining opposing cavity walls, several direct methods utilizing fibers as internal connecting or splinting elements have been put forward. So far, reinforcement with fibers has shown to enhance strength only in a narrow range of dental materials, such as composite resins [126]. In our study, two different materials, namely polyethylene fiber sheet (Ribbond THM) and a fiber glass net (everStickNET) were used in different configurations inside the cavity, with the aim of stabilizing the opposing walls and reinforcing the tooth structure. Polyethylene fibers possess a dense concentration of fixed nodal intersections that assist in maintaining the integrity of the fabric. This enables the stresses in the bulk of the material to be transferred more effectively thanks to the well-defined load paths from one area to another [127]. As shown by Eskitascioglu et al., using polyethylene fiber ribbons in combination with bonding agents and flowable composites under composite restorations may act as a stress-absorber due to their lower elastic modulus [128]. In most groups in our study, the efficacy of polyethylene fiber reinforcement did not depend on the position within the direct restoration, as there was no statistically significant difference among their fracture resistance values. This is in accordance with Akman et al., who did not find significant difference when restoring ET teeth with MOD cavities using polyethylene fibers in different configurations and positions [127]. The only exception in our study was between Group 7 and Group 11 (p=0.026), among the groups with polyethylene fibers. The use of these fibers seems to be beneficial, since groups with polyethylene fibers did not differ significantly, whereas teeth restored with composite alone showed significantly weaker fracture resistance compared to intact teeth (p=0.033). This is in contrast with the findings of Belli et al. [129, 130]. However, it must be considered that they tested the polyethylene fibers in ET and not vital teeth.

It was shown by Garoushi et al. that the addition of continuous bidirectional or short random FRC substructure under composite resin could increase the load-bearing capacity of the restoration [131]. Bidirectional fibers within the fiber glass net give orthotropic properties to the material [132]. Turkaslan et al. found that pre-impregnated bidirectional FRC can reinforce the tooth interface in two directions, distributing the stresses more evenly and increasing the toughness of the restoration by preventing crack propagation [133]. So far everStickNET has only been used beneath endocrowns and anterior veneers, but not in posterior cavities. Contrary to polyethylene fibers, the reinforcing efficacy of bidirectional fiber glass nets does not seem to vary with the position within the restoration. Group 3 showed significantly reduced fracture resistance compared to Group 5 (p=0.001) and Group 6 (p=0.000), while Group 4 was significantly weaker than Group 6 (p=0.023). While using polyethylene fibers was beneficial in all groups, fiber glass net could efficiently reinforce teeth only in Groups 5 and 6 (no significant difference from control). Interestingly, in specific positions, namely when applied bucco-lingually on the base of the cavity (Groups 3 and 7) or bucco-lingually in the coronal third of the restoration (Groups 4 and 8), the two different bidirectional materials yielded different reinforcements. Groups 3 and 4 were respectively significantly weaker than Group 7 (p=0.009) and Group 8 (p=0.049). This could be attributed to the difference in the quality and the quantity of fibers. Of all restored groups, Group 3 recorded the poorest results. This is in line with the findings of Oskoee et al. [126]. Also, Group 7 (polyethylene fibers laid down bucco-lingually on the base of the cavity, connecting the opposing walls) was found to be the weakest among the polyethylene fiber groups. The reason behind this could be that although the opposing walls were connected, the fibers were not stretched and weren't under tension at all. Previous studies have pointed out that the placement of fibers at the tensile side of composite resin specimens improves flexure properties [39, 134]. According to the results of Oskoee et al., placing a glass fiber net, to serve as an occlusal splint in the coronal third of an MOD cavity between composite layers, significantly increases fracture resistance [126]. In groups with occlusal splinting, the fibers were placed so that their ends extended until the occlusal one-third of the buccal and lingual walls of the cavity, allowing the fibers to keep the cusps together, as described by Oskolee [126] and Akman et al. [127]. In our study, regardless of the type of fiber used, its application as an occlusal splint resulted in increased fracture resistance and no significant difference from intact teeth. This is only partly in accordance with Belli et al., who's results showed increased fracture resistance with occlusally splinted groups with polyethylene fibers. Still, their restored specimens were significantly weaker than intact teeth [130]. With occlusal splinting, fibers are placed close to the point where force is exerted, which leads to a shorter working arm according to the principles of levers and centripetal actions. In addition, placing fibers on the occlusal surface keeps buccal and lingual cusps bound together, leading to higher fracture resistance [126]. Connecting the remaining opposing cavity walls can also be accomplished by circumferentially covering the rebuilt mesial and/or distal axial walls, a technique called "wallpapering" by Deliperi and colleagues [119]. So far, the use of FRC materials to circumferentially connect the walls of MOD cavities was only attempted by Daher et al. [135], but was performed externally around the coronal part of the tooth. When applied circumferentially, there was no difference between the fiber glass net and polyethylene fibers in our study. Interestingly, the net applied circumferentially (Group 6) yielded significantly higher fracture resistance than fiber glass net at the base of the cavity (Group 3, $p=0.000$) or in the occlusal third inside the filling (Group 4, $p=0.023$). At the same time, there was no statistically significant difference among the corresponding Ribbond groups (between Group 7,8,9 and 10). Also, it is worth mentioning that the fiber glass net together with SFRC placed as an occlusal splint (Group 5) or circumferentially (Group 6), was not significantly better than SFRC alone (Group 2) in terms of reinforcement. We assume that even when SFRC is used alone as dentin replacement, the randomly oriented fibers lend an isotropic reinforcement effect in multiple directions instead of only a few specific ones [62]. Also, the adaptation of SFRC alone could be better to the cavity walls. From a clinical point of view,

it is worth mentioning that the usage of SFRC alone in a bulk manner was easier and less time consuming compared to using the fiber net or the polyethylene one.
Among all restored groups, the transcoronal splinting with polyethylene fibers (Group 11) produced the highest fracture resistance, even slightly exceeding the values of intact teeth. In our opinion, this can be attributed to the fact that the polyethylene fibers are not laid down like in the other groups, but rather stretched, and put under tension. A similar concept was shown by Karzoun et al. with a FRC post penetrating through the opposing walls [136]. As the polyethylene fibers are positioned at the occlusal third of the crown, it should theoretically hold all benefits as the occlusal splinting group, namely working as an early stress-redirecting layer and producing a shorter working arm under loading. Also, the concept is considered to be biomechanically correct, as polyethylene fibers – due to their inherent dense network of locked nodal intersections – could also serve as a potential crack stopping medium, therefore could attempt to act as a potential DEJ substituting layer.

Regarding **fracture pattern**, the failure was dominantly a favorable one (above the CEJ) in most cases when fibers were incorporated into the direct restoration. The highest ratio of favorable fractures was seen with SFRC alone (Group 2), whereas composite alone (Group 1) and transcoronal splinting (Group 11) yielded the highest ratio of unfavorable fractures. This, once again, points to the increasingly recognized problem of large direct composite restorations, that is, that their fracture toughness is suboptimal, and they cannot serve as a good substitute for DEJ. This way, cracks and fractures propagate freely in the restoration, which ultimately results in non-restorable damage.

The limitation of the posterior investigation is that static load-to-fracture test was used to determine maximal fracture resistance, instead of applying cyclic loading. According to Taha et al, "In experimental studies, fracture resistance to static loading has been used as a measure of the effect of cavity preparation and/or restoration on tooth strength. Although the fracture load is typically much higher than functional occlusal loads, it is still a valid method for comparing restorative materials and different cavity designs." [117]. Also, as stated by Le Bell-Rönnlöf et al., static loading is usually the first step in the evaluation process of novel dental materials and related techniques and is commonly used in order to obtain basic knowledge regarding the fracture behavior and load capacity of restored teeth [98]. Given the mentioned shortcomings, the proposed techniques should require future testing with cyclic dynamic loading, as in the case of our study with anterior teeth.

Conclusions

- The restoration of immature anterior teeth with the use of flowable SFRC as post-core material displayed promising performance in terms of fatigue resistance and survival.
- Microgap formation within the root canal does not seem to show direct correlation with fatigue survival values in case of immature anterior teeth.
- Surface microhardness values of the tested restorative materials decreased as the depth increased in the root canal.
- The surface microhardness values of SFRC materials utilized in the Bioblock technique were comparable to dual-cure materials within the root canal.
- Deep MOD cavities in non-root canal treated molars can be reinforced with fibers utilized in direct restorative techniques.
- Regarding fracture resistance, the use of polyethylene fibers seems to always be beneficial in the direct composite restoration of deep MOD non-root canal treated molars, regardless of position within the cavity or the restoration itself.
- Regarding fracture resistance, the efficacy of glass fiber net used together with SFRC for restoring non-root canal treated molars with large MOD cavities is highly dependent on the position of the net within the cavity or the restoration,
- Bulk-applied SFRC (to substitute dentin and the DEJ) covered with composite can reinforce deep MOD cavities in non-root canal treated molars.
- If fracture occurs within direct composite restorations used for the restoration of deep MOD cavities in non-root canal treated molars, it is predominantly an unfavorable (irreparable) fracture.

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