The Restorative Use of Fibre-Reinforced Materials in the Posterior Region

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. **Fráter M**, Forster A, Keresztúri M, Braunitzer G, Nagy K. In vitro fracture resistance of molar teeth restored with a short fibre-reinforced composite material. J Dent. 2014 Sep;42(9):1143-50. doi: 10.1016/j.jdent.2014.05.004. Epub 2014 May 21. PubMed PMID: 24859462. **IF : 2.749** (2014)

II. **Fráter M**, Forster A, Jantyik Á, Braunitzer G, Nagy K. Flexibilis és merev üvegszál megerősítésű intraradikuláris csapok törési ellenállásának in vitro összehasonlító vizsgálata - pilot study. *Fogorvosi Szemle* 2015.

Related publications:

1. **Fráter M**, Braunitzer G, Urbán E, Bereczki L, Antal M, Nagy K. In vitro efficacy of different irrigating solutions against polymicrobial human root canal bacterial biofilms. Acta Microbiol Immunol Hung. 2013 Jun;60(2):187-99. doi: 10.1556/AMicr.60.2013.2.9. PubMed PMID: 23827750**. IF : 0.78** (2013)

Introduction

To find the ideal material(s) for the restoration of posterior teeth (premolars and molars) has long been a central issue in restorative dentistry. To be able to fabricate a perfect restoration, one must be aware of the potential risk factors and characteristic types of failure in the region. Two main causes of posterior restoration failure have been identified: fracture (either of the restoration or the tooth itself) and secondary caries. Of these, secondary caries poses the greater threat. In a review by Brunthaler and colleagues, it was shown that early failure was more closely related to fractures, while caries was more likely to be the background of long-term failure [1]. Da Rosa et al. and Pallesen et al. came to an opposing conclusion: in their long-term studies (with more than 10 years of follow-up) they found that failure was more frequently the result of fracture than of caries [2-4]. This latter result suggests that fracture is also a considerable threat to posterior restorations, regardless of the lifespan or the age of these restorations.

The question arises whether we should apply a direct or an indirect restoration. Direct restorations have been widely applied to restore posterior teeth due to their low cost, the smaller amount of healthy tooth substance that has to be removed as compared to indirect restorations, and their acceptable clinical performance [5, 6]. Thus, emphasizing the daily clinical relevance of this topic, this thesis is limited to the direct restorative solutions of the posterior region. 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, composite restorations are more favourable in some respects. These include better aesthetics, adhesive properties that allow a reduced preparation size [7] and the reinforcement of the remaining dental structure [8]. The latter has been thoroughly addressed in other studies. Versluis and co-workers found that an unbounded amalgam filling generated stresses in the tooth comparable to as if the cavity had been left empty, and when loaded, the amalgam did not take over the load previously carried by the lost healthy tooth structure [9]. This was further confirmed by Magne et al. who showed that amalgam fillings in Class I and Class II cavities could not substitute the missing dental tooth structure in terms of biomechanical features and could not reinforce the tooth [10]. These findings could partly account for the phenomenon that complete cusp fracture of posterior teeth, especially with class II amalgam restorations, is quite common, with incidence rates varying from 20.5 to 71 per year per 1000 person at risk [11]. In the same study, Magne et al.

also pointed out that composite direct restorations behaved much more favourably under the same conditions [10]. It has been put forward in some studies that by the application of the direct and indirect adhesive techniques, the internal strength of teeth can be reinforced [12, 13]. Resin bonded composite restorations showed a strengthening effect on the tooth structure, with fracture resistance close to that of unaltered or unrestored teeth [14-16].

According to the principles of modern restorative dentistry, the restoration and the tooth should form a structurally adhesive and mechanically unified medium, which has the ability to withstand repetitive multi-axial bio-mechanical force loads over a prolonged period of time. The definition of the term “biomimetic” in the field of restorative dentistry is the study of the structure, function, and biology of the tooth organ as a model for the design and engineering of materials, techniques, and equipment to restore or replace teeth [17]. In practice, 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 regarding their mechanical features and properties.

In order to do so one must understand the histological structure and the biomechanical properties of the dental tissues. Enamel, the outer barrier, is capable of resisting a wide range of challenges from the oral environment (i.e. mechanical, chemical, biological and thermal) for one’s entire life [18]. It acts as a shield that protects the softer underlying dentine against wear [19]. Brittle yet stiff, enamel undergoes only minimal deformation while transferring loads to the underlying dentine [20]. Dentine possesses both elastic and plastic properties and provides the support for the enamel dome. Table 1. summarises the mechanical properties of enamel and dentine (see below). A typical biomimetic restorative approach is the combined use of materials to replace the different tissues, such as the use of porcelain to replace enamel and composite resins to replace dentine, combined with optimised bonding strategies [21, 22]. Other factors must also be taken into consideration, though. A thorough histological examination of the tooth reveals a third type of tissue (or layer): the dentine-enamel junction (DEJ). The DEJ has been histologically described as an interphase between the two bio-mechanically vastly different tissues. The natural adhesion measured between enamel and dentine resulting from the presence of the DEJ is around 47,7-51,5 MPa [23]. This can be reached with the use of modern adhesives. According to what has been said so far, one could say that an ideal restoration would be a bonded porcelain restoration substituting the missing enamel layer, and if dentine also needs to be replaced, composite resin should be used under the porcelain coverage. Logical as it may sound, the use of this approach is limited in practice, due to both financial and technical limitations. One notable limitation is that modern composites are becoming less and less elastic. In fact, they are now in the range of feldspathic porcelains.

With their improved mechanical properties and wear resistance, and given their more favourable cost, resin composites have, for many, become the material of choice not only for dentine replacement, but also for the restoration of the whole posterior tooth in the posterior region [24]. At the same time, polymerization shrinkage is a critical limitation of dental composites. During the setting reaction in the pre-gel phase, the material is able to flow and stresses can be distributed more evenly [25, 26]. Conversely, the post-gel polymerization results in stresses in the structure of the tooth and also in the tooth-material bonding interfaces [27-29]. Dental composites exhibit 0.5–4% shrinkage in linear measurements [30, 31], while the volumetric shrinkage ranges from 2% to 6% [32]. Such shrinkage is clinically unfavourable, as it puts stress on the vulnerable bonding interface [33]. These stresses may be transferred through bonding to the tooth structure, which may lead to the deformation of the tooth walls, cuspal deflection and/or enamel cracks [34-36]. When the contraction stress overcomes the bond strength, interfacial sealing is lost, which results in post-operative sensitivity, marginal staining and secondary caries [37], or even pulp necrosis. Studies have shown that the magnitude of the contraction stress is affected by the configuration of the cavity, the volume of the applied material, and the filling technique [29, 37, 38]. Clinically, it is widely recommended to use an incremental layering technique in order to reduce the polymerization stress [24, 29, 38] and to develop better mechanical properties [39, 40]. The latter is accomplished by decreasing tensile stress concentrations at the restoration interface [41] and reducing the cuspal strain [42]. Some studies suggest that oblique layering strategies are superior to horizontal layering strategies [43], while others studies found no significant difference in this respect [44]. The latter observation is in accordance with studies showing that the magnitude of the cuspal deflection was not significantly different when different layering techniques were used [45, 46]. In spite of the fact that many studies recommend oblique layering in order to avoid or delay the bonding together of opposing cusps, thereby reducing the stress levels within the restoration and at the tooth-composite interface [47, 48], it is still not yet clear which of the incremental techniques is the most appropriate.

Fracture occurrence remains a problem, even when adhesive (direct or indirect) restoration is done. In the case of direct restorations, fracture of the restoration or the surrounding tooth structure is a result of multiple factors, including fracture propagation through the composite material, which results in extremely high dislodging forces at the bonding interface between the restoration and the tooth structure [49]. The greater the axial measure (depth) of the restoration, the greater the dislodging forces are at the restoration-tooth interface due to the extended load arm of the occlusal load. Due to an excessive loss of tooth structure, loss of the marginal ridge(s) and a significant loss of rigidity at the coronal part, and in spite of the middle range C-factor, the indications and long term prognosis of medium-sized and large class II MOD composite restorations are a matter of debate [50].

As mentioned earlier, the adhesive and connecting properties of the DEJ can be mimicked, and therefore DEJ substitution is partly possible, but a further problem has to be taken into consideration. Stress transfer in simple bilaminate structures with divergent mechanical properties usually induces increased focal stresses at the interface [51]. In these cases the generated stress tends to accumulate in the softer tissue of the two connected ones [52]. If enamel and dentine comprised a simply bonded bilamine at the functional surfaces of the tooth, enamel cracks would easily propagate into dentine, but this is not quite the case in healthy teeth. The excellent biomechanical properties of the DEJ can divert and blunt enamel cracks through considerable plastic deformation [53], providing a functional shielding mechanism and allowing synergy between enamel and dentine. This is the mechanism that enables these natural tissues to withstand a lifetime of mastication. Although multiple cracks can be seen in the enamel of aged teeth, they rarely affect the integrity of the DEJ or reach and compromise the supporting dentinal base. Therefore, DEJ might be considered a specialised tissue type of its own right, serving a fundamental function, and when restoring a tooth according to biomimetic principles, one should also consider this layer, not only dentine and enamel [54]. The rationale of mimicking DEJ during the restorative process is to prevent crack propagation into the deeper layers of the restoration during mechanical overload, thus minimizing the cantilever that acts to separate the restoration. In conventional composite restorations a crack spreads to the restoration-dentine interphase, forming a major cantilever attacking the bond layer, and finally dislodging the separated fragment of the restoration. In 2011 a short fibre reinforced composite (SFRC) (EverX Posterior, GC Europe, Leuven) was introduced to the market with the goal not only to change restorative indications of large class II posterior cavities towards direct restorations, but also to mimic the stress absorbing properties of the DEJ.

Utilizing different types of fibres with various orientations and lengths is quite an old idea in engineering and in architectural applications to construct devices with high strength and fracture toughness. "*And Pharaoh commanded the same day the taskmasters of the people, and their officers, saying, Ye shall no more give the people straw to make brick, as heretofore: let them go and gather straw for themselves*". One of the most ancient use of fibres as a reinforcement is reported in the book of Exodus of the Holy Bible, when Israelites used straw to reinforce their bricks made of clay almost 4000 years ago. The first glass fibre reinforced boat was produced in 1937 in Russia and since then the anisotropicity of fibre reinforced materials has been used in everyday life and recently in medicine. In dentistry, attempts to apply glass fibres to reinforce dental polymers have been made for over 30 years [55]. Glass fibres have been documented to be superior to carbon or aramid fibres in terms of reinforcing efficiency and aesthetic qualities [56-58]. The rationale behind the usage of fibre reinforcement is partly to internally strengthen the structurally compromised tooth and partly to prevent the occurence of fractures [59].

The efficacy of fibre reinforcement is dependent on several factors, including the resins used, the length of the fibres, the orientation of fibres, the position of the fibres, the adhesion of the fibres to the polymer matrix, and the impregnation of the fibres into the resin [60]. The reinforcing effect of the fibre fillers is based on stress transfer from the polymer matrix to the fibres, but the individual fibres also act as crack stoppers. Stress transfer from the polymer matrix to the fibres is essential [61]. This is only possible if the fibres have a length equal or greater than the critical fibre length [62]. The critical fibre lengths of E-glass with bis-GMA polymer matrix vary between 0.5 and 1.6 mm [63]. Also, the position and orientation of the reinforcement within a structure is known to influence its mechanical properties [64]. When force is applied perpendicular to the long axis of a directionally oriented fibre, strength reinforcement occurs. Forces result in matrix-dominated failures if applied parallel to the long axis of the fibres [65]. Unidirectional continuous fibres provide reinforcement in one direction, bidirectional or woven continuous fibres provide reinforcement in two directions and randomly oriented fibres lend an isotropic reinforcement effect [66]. The reinforcement per direction is however less effective in the later one, since a certain volume of fibres is divided into multiple directions [11]. E‑glass fibres have a demonstrated ability to withstand tensile stresses and hold the potential to stop crack propagation in composite materials. The recently introduced SFRC (EverX Posterior, GC Europe, Leuven) restorative material is intended to be used in high stress bearing areas especially in molars. It consists of a combination of a resin matrix, randomly orientated E-glass fibres and inorganic particulate fillers. The resin matrix contains bis-GMA, TEGDMA and PMMA forming a matrix called semi-Interpenetrating Polymer Network (semi-IPN) which provides good bonding properties and improves the toughness of the polymer matrix [61].

The use of SFRC as a dentine substituting agent could be beneficial in the case of large posterior restorations. As previously shown by Magne and colleagues, losing the marginal ridges in posterior teeth leads to great deflection of the opposing oral and vestibular walls [10]. As pointed out by El-Helali et al. [67], standardised MOD cavity preparation in maxillary premolar teeth was shown to result in an average loss in relative cuspal stiffness of 63%, which is related principally to the loss of marginal ridge integrity. This is in accordance with the findings of Reeh et al. [15] who measured a loss of tooth stiffness of about 20% in the case of an occlusal endodontic access cavity, compared to a 63% loss for a deep MOD cavity. Later, other laboratory tests confirmed this [68, 69]. A large MOD cavity preparation could be considered to be typical of an amalgam replacement with the indication of an indirect or large direct restoration, which is becoming quite widespread [70]. It is interesting to note that once an MOD cavity had been prepared, meaning both marginal ridges are lost, an additional endodontic access preparation did not significantly influence the relative cuspal stiffness when the access cavity was confined to the occlusal floor [15, 71]. Therefore, it is highly important to preserve as much tooth structure as possible both in vital and in endodontically treated teeth. Endodontically treated teeth (ETT) are structurally different from non-restored vital teeth, and they require specific restorative treatment [72]. The differences include reduced moisture and dentine fracture resistance and decreased proprioception [73]. According to Dietschi et al. [74], the consequences of these changes are negligible in clinical settings. The major issues with ETT seem to be the coronal destruction by caries, fractures of previous restorations, dentine loss due to the removal of the roof of the pulp chamber [75], and the weakening of the peri-cervical dentine during access preparation [76]. As a result of the compromised structural integrity, an increased fracture tendency during normal function is seen [77]. Thus, in most ETT, the use of intraradicular posts is recommended to promote the retention of the final restoration and to biomechanically reinforce the remaining tooth structure [78]. However it has to be stated that if ETT still have substantial amount of remaining sound tooth structure, posts are not improving longevity of ETT but bear substantial risks when placing them [79, 80]. In an attempt to address the problem of compromised structural integrity in ETT, fibre reinforced composite (FRC) materials have been incorporated into root canal posts and their improvement and use has increased rapidly over the last 10 years [81]. Generally, composite luting cements are used to adhesively bond the fibre posts to the root canal dentine. This adhesion is compromised by several factors, most importantly by the difficulty of applying the adhesive into the narrow root canal and by the high c-factor (more than 200 in the root canal), which can easily lead to debonding [82]. This was confirmed by several in vitro tests, underlining the role of mechanical frictional retention in the stability of the post [83]. Recent studies have shown that post space preparation weakens the remaining tooth structure further, thus paradoxically, the conventionally accepted process of strengthening the tooth may cause further increase in root fracture risk [84]. These findings underscore the importance of trying to preserve the original anatomy of the root canal and minimizing dentine loss throughout the endo-restorative treatment. This leads to unique and irregular root canal forms in several cases, in which one, fully insertable FRC post cannot provide adequate mechanical friction on its own. Utilizing multiple posts to treat wide, irregular endodontic cavities has already been proposed when restoring ETT [85]. However, the use of this technique is limited when applying a minimally invasive approach in post space preparation.

To overcome the difficulties that irregular root canal forms pose, an elastic FRC post (everStick POST, GC Europe, Leuven) was introduced to the market in 2011. This post, made of a polymethyl methacrylate (PMMA) based, semi-interpenetrating polymer network (semi-IPN) matrix has similar mechanical and chemical properties as the SFRC EverX Posterior. The post is individually adaptable and it's bonding and flexural properties appear to be superior to commercially available, prefabricated FRC posts [81].

The question arises whether these new FRC materials are able to reinforce the dental structure and lead to more favourable fracture resistance and fracture patterns when applied according to biomimetic principles, in the case of vital and endodontically treated teeth.

The first goal of the in vitro studies presented here was to assess the effect of SFRC restorative composite materials on the biomechanical stability of molar teeth restored with a large class II MOD composite filling, utilizing different layering strategies. The second goal was to determine and compare the fracture resistance and fracture patterns of endodontically treated premolar teeth restored with different FRC posts in different configurations.

Dental hard tissue	**Elastic modulus (GPa)**	**Thermal expansion coefficient (x10^{-6}/°C)**	**Ultimate tensile strength (MPa)**
Enamel	80	17	10
Dentine	14	11	105

Table 1. Physical properties of dental hard tissues according to Magne et al. [19].

Methods

All procedures of the study were approved by the Regional Ethics Committee for Human Medical Biological Research (University of Szeged, Hungary) and the study was designed in accordance with the Declaration of Helsinki in all respects. One hundred and thirty mandibular 3rd molars and fifty upper premolar teeth extracted for periodontal or orthodontic reasons were selected for this study. The freshly extracted teeth were immediately placed in 5.25% NaOCl for 5 min and then stored in 0.9% saline solution at room temperature until use all within 6 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 or root cracks, absence of previous endodontic treatment, posts or crown or resorptions. Furthermore, buccolingual and mesiodistal radiographs were taken of all premolar teeth and examined to evaluate root integrity and the number of canals present.

To standardize procedures and materials as much as possible, all molar teeth were rather similar regarding their coronal portions and all premolar teeth were rather similar for their root parameters. Premolar teeth included in this study had 1 root canal in each root with a curvature of less than 5°, evaluated by Schneider’s technique [86], and root length of 15+/-1 mm and rather similar mesiodistal and buccolingual dimensions (+/-10%) were selected.

Regarding the coronal portion of molar teeth about 80% of the specimens ranged 10.0–10.9 mm in size, measured at the widest bucco-lingual dimension, and the rest were between 11.0 and 12.0 mm. Molar teeth with severe polymorphism of the coronal structures were excluded from the investigation. From this point of the investigation premolar and molar teeth were kept and dealt with separately.

As mentioned in the Introduction, the study sought to examine two main aspects of tooth restoration. Accordingly, the examinations were carried out in two phases. In the first phase, the crowns of molar teeth were restored with different composite materials applied according to different techniques, and no root canal treatment was performed. In the second phase, the effects of root canal treatment plus post placement with different types of posts was examined in premolar teeth.

Crown restoration in molars

Cavity preparation Standardized MOD cavities were prepared by the same trained operator according to Cara et al. [70] in four groups of the five, and one group was left intact to serve as control. In these standardized cavities the bucco-lingual width (BLW) of the approximal box of each cavity was prepared to two-thirds of the BLW of the tooth, and the occlusal isthmus was prepared to half the BLW. In addition, the cavity depth at the occlusal isthmus was also standardized to 3.5 mm from the tip of the lingual cusp and 1 mm above the CEJ at the cervical aspect of the approximal boxes. In order to exclude measurement error due to non-uniform cavity preparation, the approximal depth of each cavity – from the neighbouring functional cusp tip to the gingival floor of the approximal box – was measured manually, with a 15 UNC periodontal probe (Hu-Friedy Mfg. Co., Chicago, USA). In 90% of the cases, the approximal depth was 6 mm, and the remaining 10% measured five or seven millimetres. The mean depth of the cavities turned out to be 6.02 mm with a standard deviation of 0.32. Considering that the 5- and 7-mm-deep cavities, that added up to a total of 10% of the entire sample, were distributed among the study groups, it can be concluded that the chance of measurement error due to this factor was negligible. The cavosurface margins were prepared at 908 and all internal line angles were rounded. Further consistency in cavity preparation was ensured by parallel preparation of the facial and lingual walls of the cavity (Fig. 1). The cavity was rinsed with water and air-dried with an air/ water syringe. After application of a Tofflemire (1101C 0.035, Hawe-Neos, Italy) matrix band, the enamel was acid-etched selectively with 37% phosphoric acid for 15 s, rinsed with water and air-dried. The cavity was adhesive-treated with Unifil Bond (GC Europe, Leuven, Belgium) according to the manufacturer's instructions. The adhesive layer was light-cured for 40 s with an Optilux 501 halogen light (Kerr, Orange, CA, USA) operating in standard mode at a light intensity of 740+/-36 mWcm2. 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, serving as an intermediate layer for the SFRC or future composite layers. This layer was light-cured for 40 s. After the application of the flow composite, the cavities were restored with either SFRC (EverX Posterior, GC Europe, Leuven, Belgium) and dental composite (G-aenial Posterior, GC Europe, Leuven, Belgium) or only dental composite (G-aenial Posterior) as follows:

- Group 1/a, 2/a: Horizontal incremental technique. SFRC or composite was placed in two consecutive maximum 2 mm-thick horizontal layers. Each increment was light cured from the occlusal surface for 40 s each. After removal of the Tofflemire matrix band the mesial and distal sides were light cured for 20 s each (total 80 s).
- Group 1/b, 2/b: Oblique incremental technique. SFRC or composite was placed in several consecutive 2 mm-thick oblique increments. Each increment was light cured from the occlusal surface for 40 s each. After removal of the Tofflemire matrix band the mesial and distal sides were light cured for 20 s each (total 80 s). In groups 2/a and 2/b (sample size: 26 teeth/group) the cavities were filled according to the anatomy of the dentine with SFRC, except for the last 1 mm measured from the occlusal surface, leaving 1 mm occlusally for the final composite layers as prescribed by the manufacturer. Each layer was light cured from the occlusal surface for 40 s each. After removal of the Tofflemire matrix band the mesial and distal sides were light cured for 20 s each (total 80 s). Finally, the restoration was finished with a fine granular diamond burr (FG 7406-018, Jet Diamonds, USA and FG 249-F012, Horico, Germany) and Soflex disks (3 M ESPE, USA).

Post placement in ETT premolars

Before root canal treatment, all crowns were sectioned at the level of the cementoenamel junction (CEJ) perpendicular to the longitudinal axis, using a slow-speed, water-cooled diamond disc (40000 rpm).

At the beginning of the root canal treatment the working length was established using a direct method, by subtracting 1 mm from the actual root length determined by introducing a no. 10 K-file (Maillefer-Dentsply, Ballaigues, Switzerland) until it was visible through the apical foramen. A crown down technique was used for instrumentation with Gates Glidden (Union Broach, York, PA) #2 to #4 drills and then the canals were instrumented using rotary ProTaper files (Dentsply, Maillefer, Ballaigues, Switzerland). The series of the ProTaper system (S1, S2, F1, F2, F3) was used for the preparation at the working length.

Irrigation was performed after every change of instrument with 2 milliliters of 2.5% NaOCl solution and the canal space was filled with irrigant during the instrumentation phase. A root canal lubricant (Glyde, Dentsply-Maillefer, Konstanz, Germany) was only used during the shaping of the coronal third. After shaping and cleaning, the roots were dried with 96% alcohol and paper points. Root canal filling was performed by matched-single-cone obturation with a master cone (F3 gutta-percha, Maillefer-Dentsply, Ballaigues, Switzerland) matching the final instrument used for preparation and sealer (AH plus; Dentsply De Trey GmbH, Konstanz, Germany). The root access was temporarily filled with Clearfil SE Bond and Clearfil AP-X (Kuraray, Tokyo, Japan). The same composite was applied to the apical part of the root in order to prevent leakage through the apex. The teeth were then stored in an saline for 1 week. After 1 week of storage, post space was prepared in the root portions of the teeth with a depth of 10 mm, as measured from the CEJ on the buccal aspect of the tooth, but no post space preparation drill was used so that the individual anatomy could be preserved. Only the root canal filling was removed with size 3 Gates Glidden burs and ISO standard Hedstrom files, leaving a minimum apical seal of 4-6 mm of gutta-percha in the canal.

For the restorations, two different types of FRC posts were used: a prefabricated, conventional “rigid” FRC post (0,8 GC Fiber Post, GC Europe, Leuven, Belgium) and an elastic FRC post (0,9 EverStick POST, GC Europe, Leuven, Belgium).

The conventional translucent FRC posts of 0.8 mm diameter (Fiber Post) were tried in and cleaned with alcohol afterwards. The posts did not receive any surface treatment. The elastic FRC posts were handled according to the manufacturer’s instructions, with sterile tweezers. Regardless of the exact type, the main posts were placed in a way that 5.0 mm was left above the level of decoronation, and 10.0 mm was inserted into the root canal. This way, a uniform 15.0 mm fibre length was achieved.

The teeth were randomly distributed in 5 study groups, each group consisting of 10 teeth.

- Group 1 received one single conventional FRC post (0.8 mm).
- Group 2 received one main conventional FRC post and one collateral post (0.8 mm both) using a “multi-post technique”. The collateral post was inserted next to the main post as apically as possible without causing manually perceivable stress but it was always deep enough to wedge the main post in the canal.
- Group 3 received one single elastic FRC post (0.9 mm). As according to the manufacturers’ instructions, the post was inserted into the root canal, and adapted to the form of that. Once adapted, the post was removed from the root canal with a needle-nose plier and light cured for 40 seconds so that it would retain the shape of the canal.
- Group 4 received one main elastic FRC post and one elastic collateral post (0.9 mm both) using a multi-post technique. The collateral post was inserted next to the main post as apically as possible without causing manually perceivable stress. The posts were removed as one unit from the root canal with a needlenose plier and then light cured for 40 seconds maintaining their position together in the canal.
- Group 5 received as many elastic FRC posts (0.9 mm) as possible bundled according to the thickness of the root canal using the lateral condensation method described by Hatta et al. [87]. These posts were gently removed as one unit with a needlenose plier from the root canal, and then light-cured for 40 seconds. It was confirmed in all cases that the elastic FRC posts were repositioned to their original position into the canal after light-curing. If resistance was met, the post surface was adjusted using carborundum point.

During the luting procedures all groups received the same adhesive treatment by the same trained operator who completed a three year specialization in restorative dentistry.

For bonding, a dual-cure one-step self-etch adhesive system (Gradia Core Self-Etching Bond, GC Europe, Leuven, Belgium) was used, according to the manufacturer's instructions. Equal amounts of the A and B components were mixed for 5 s. The mixture was then applied to root canal dentine in the post space for 20 s using a microbrush-X disposable applicator (Pentron Clinical Technologies, LLC, USA). Excess adhesive was removed by suction drying (Evacuation Tip - Vented, Starryshine, Anaheim, CA, USA) within 0.5 cm from the dentine surface (without contact). Excess adhesive resin at the bottom of the canal was removed with a paper point. The adhesive was then light-cured for 60 s using an Optilux 501 quartz-tungsten-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 820.75 +/-16.8 mW/cm2.

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(s), 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).

In order to ensure the uniformity of the specimens, the composite resin core build-ups were standardized using cellulite core-forming matrices of the same size. These matrices were fabricated as swedged foils by a dental technician modeled on one healthy premolar tooth, which was previously prepared for a crown with a one millimeter shoulder. The core build-up was prepolymerized for 20 seconds, then glycerine gel (DeOx Gel, Ultradent Products Inc., Orange, CA) was applied and final polymerization was performed from each side for 40 s with an Optilux 501 quartz-tungsten-halogen light-curing unit.

After the restorative procedures all teeth were stored in physiological saline solution.

To simulate the periodontal ligament, the root surface of both premolar and molar teeth was coated with a layer of liquid latex separating material (Rubber-Sep, Kerr, Orange, CA) prior to embedding. Specimens were embedded in methacrylate resin (Technovit 4004, Hereus-Kulzer) at 2 mm from the CEJ to simulate the bone level (Fig.2.).

All prepared specimens were tested for fracture toughness within 24 h of restoration, using a universal loading device (Lloyd 1000R, Lloyd Instruments Ltd, Fareham, UK), according to the method described by Wu et al. [88].

In case of the molar teeth the test was performed at a cross-head speed of 2 mm/min and load was applied using a 4.8 mm diameter stainless-steel ball-shaped stylus which was positioned at the centre of the occlusal surface of the tooth crown between the buccal and oral cusps.

This was changed for the premolar teeth as each test was performed at a cross-head speed of 0.5 mm/min and load was applied at 45° using a stainless-steel ball-shaped stylus.

A force vs. extension curve was dynamically plotted for each tooth (see Fig. 3). Fracture threshold – defined as the load at which the tooth-restoration complex exhibited the first fracture, resulting in a peak formation on the extension curve – was recorded in Newtons (N). After the mechanical testing, the specimens were examined for fracture patterns. After Scotti and co-workers [89], distinction was made between restorable or non-restorable fractures under optical microscope with a two-examiner agreement (Fig. 4). A restorable fracture is above the CEJ, meaning that in case of fracture, the tooth can be re-restored, while a non-restorable fracture extends below the CEJ and the tooth is likely to be extracted [90]. Statistical analysis was conducted with SPSS 17.0 (SPSS Inc., Chicago, USA).

In the case of the molar specimens, as the Shapiro–Wilk test indicated that the data did not follow normal distribution in any of the groups, the non-parametric Kruskal–Wallis ANOVA with post hoc rank test was utilized for the comparisons.

Regarding the premolar specimens, as the data were not normally distributed in all groups, the comparisons were performed with Kruskal-Wallis ANOVA with post-hoc pairwise comparisons. The level of significance was set at $p<0.05$.

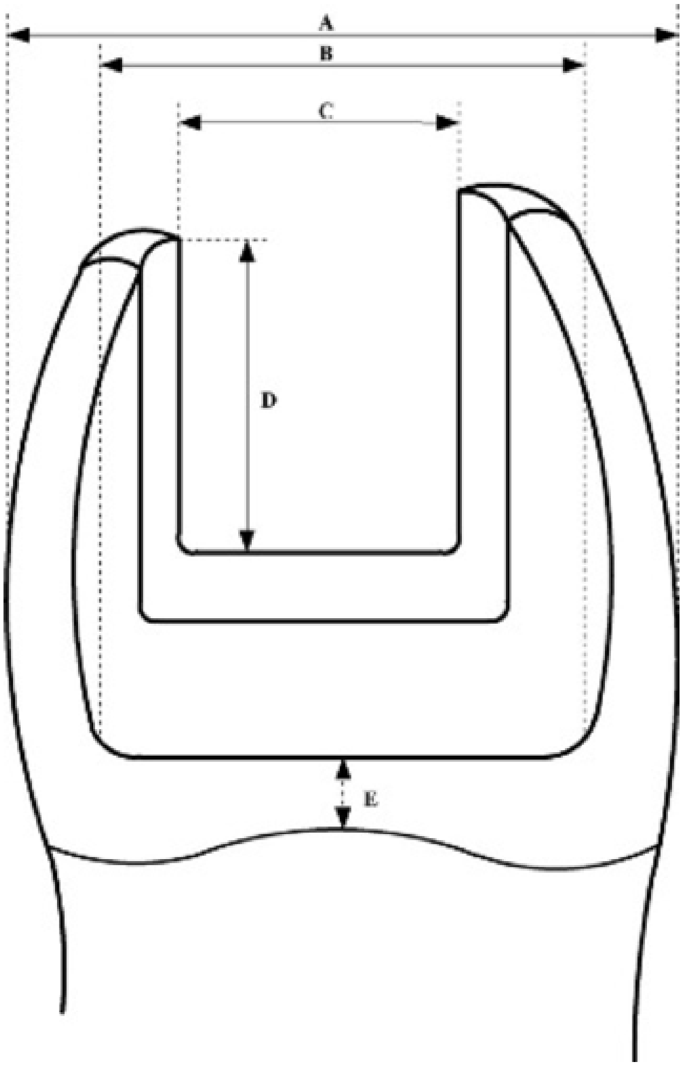

Figure 1. Schematic representation of the standardized MOD cavity; (a) the maximum bucco-lingual width of the tooth (BLW); (b) the bucco-lingual width of the gingical floor of the approximal boxes; (c) the occlusal isthmus width; (d) the cavity depth at the occlusal isthmus and (e) the cervical aspect of the approximal boxes. Image based on Figure 1 in Cara et al. [70].

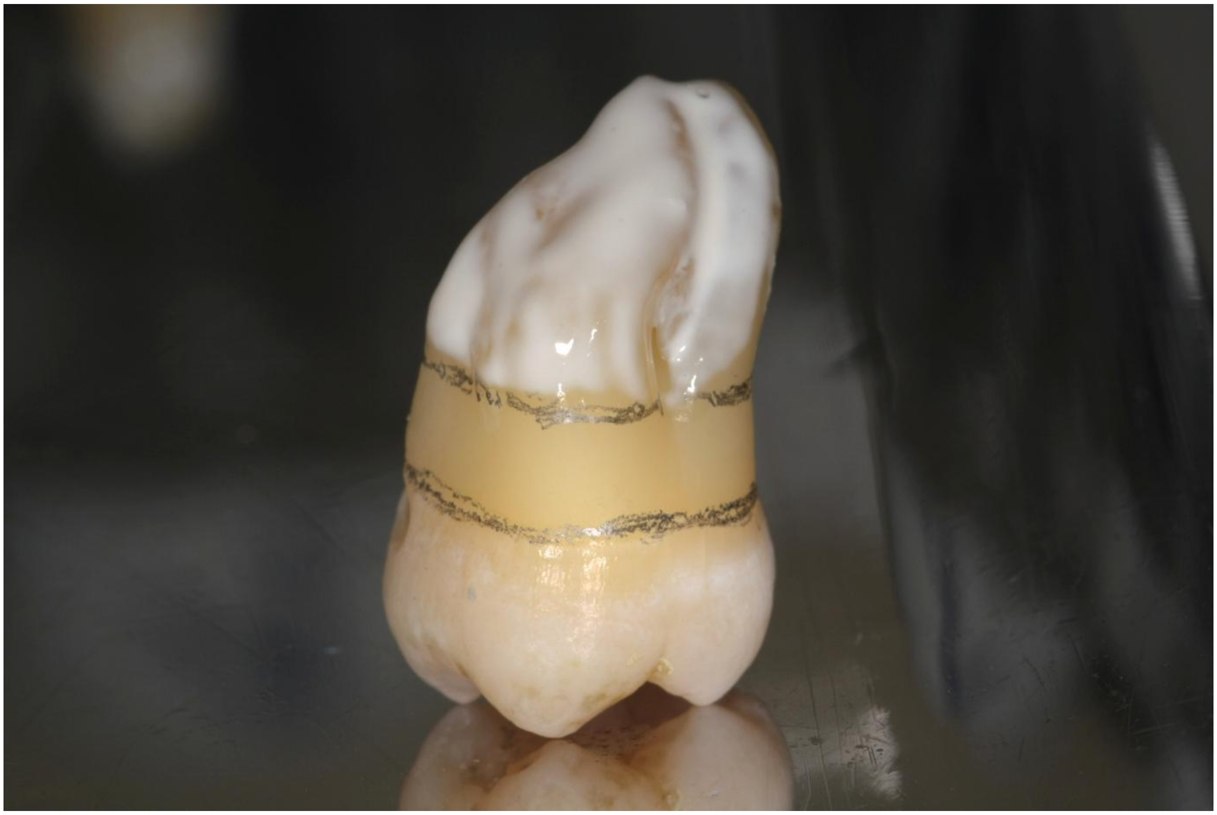

Figure 2. Applied Rubber-sep (Kerr) to simulate the periodontal ligament up to 3 mm below the CEJ.

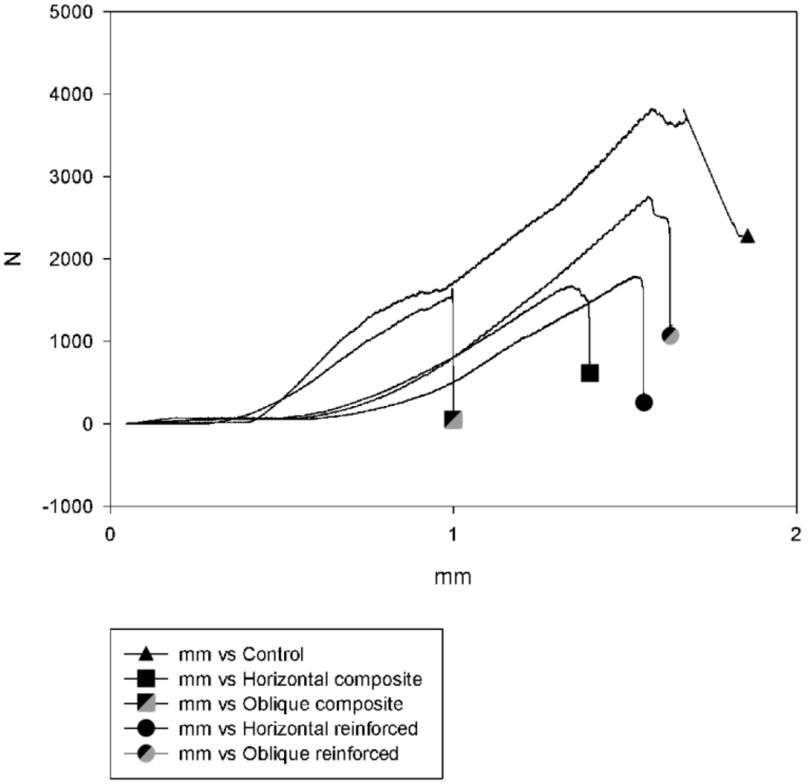

Figure 3. Force vs. extension curves of randomly chosen specimens from each study groups from the molar specimen. Peaks indicate the fracture threshold.

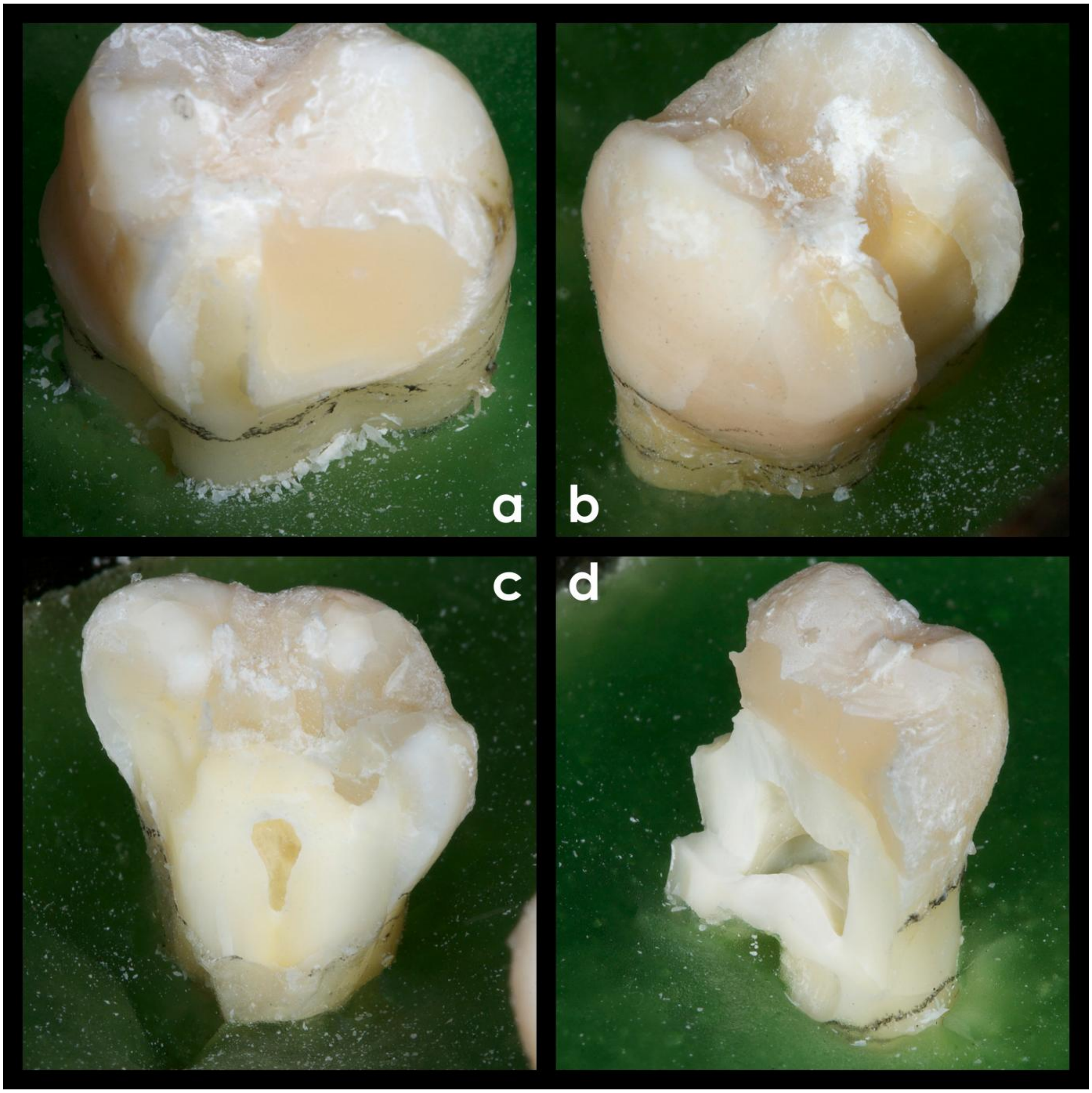

Figure 4. Examples of failed molar specimen. (a) and (b) Favourable, restorable fractures, where a small to mediate portion of the coronal part is fractured; (c) pulpal involvement, but the fracture is still above the CEJ; (d) worst case, when the fracture is below the CEJ and involves the root, making the fracture completely unrestorable.

Results

Table 2 summarizes the fracture thresholds for the different molar study groups. As the table shows, the control group exhibited the highest fracture resistance. The application of non-reinforced composite with a horizontal technique yielded a significantly poorer resistance. However, the rest of the groups did not prove to be significantly different from the control group (or from each other) in terms of fracture resistance (see Table 3). It is true that reinforced composite turned out to be superior to non-reinforced composite, regardless of the technique of application, this difference was not statistically significant. Therefore, the null hypothesis was accepted. However, it must be noted that only the reinforced composite applied in oblique increments yielded restorable fracture patterns above chance level (see Table 4).

Group	N	Mean	Minimum	Maximum	SD
Control	26	2116.74	1129.53	3796.77	788.96
Composite-horizontal	26	1444.61	471.12	3129.96	624.59
Composite- oblique	26	1517.34	667.19	2311.71	526.18
Reinforced composite-horizontal	26	1843.55	793.08	2942.28	595.98
Reinforced composite-oblique	26	1932.41	764.85	2988.82	733.24

Table 2. Maximum loads in the different molar study groups. The values are given in Newtons.

Group	C	CH	CO	RCH	RCO
Control (C)	-	0.013107*	0.070475	1.000000	1.000000
Composite-horizontal (CH)	0.013107*	-	1.000000	0.201901	0.123086
Composite- oblique (CO)	0.070475	1.000000	-	0.712696	0.472412
Reinforced composite-horizontal (RCH)	1.000000	0.201901	0.712696	-	1.000000
Reinforced composite-oblique (RCO)	1.000000	0.123086	0.472412	1.000000	-

Table 3. Comparisons between the molar study groups (Kruskal-Wallis ANOVA, p values from the post-hoc rank test). *indicates significant difference at the level $p<0.05$.

	Restorable	Non-restorable
Control	20 (77%)	6 (23%)
Non-reinforced horizontal	12 (46%)	14 (54%)
Non-reinforced oblique	13 (50%)	13 (50%)
Reinforced horizontal	13 (50%)	13 (50%)
Reinforced oblique	16 (62%)	10 (38%)

Table 4. The distribution of fracture types among the molar study groups.

The mean fracture resistance (N) and the SD for each of the five experimental conditions among the restored premolar teeth are presented in Figure 4. As the figure shows, group 4 (containing one main and one elastic FRC post) showed the highest average fracture resistance, however, this difference was only significant compared to group 1 (containing a single rigid FRC post) (p=0.027). Group 2 (containing one main and one collateral rigid FRC post) showed significantly higher fracture resistance compared to group 1 (p=0.038). However, neither of the multi-post techniques yielded significantly better results than the single elastic post technique. There was no statistically significant difference when comparing the rest of the groups regarding their fracture resistance.

In terms of fracture patterns, the tested premolar groups were almost perfectly identical (see Table 5). The null hypothesis regarding fracture patterns was accepted.

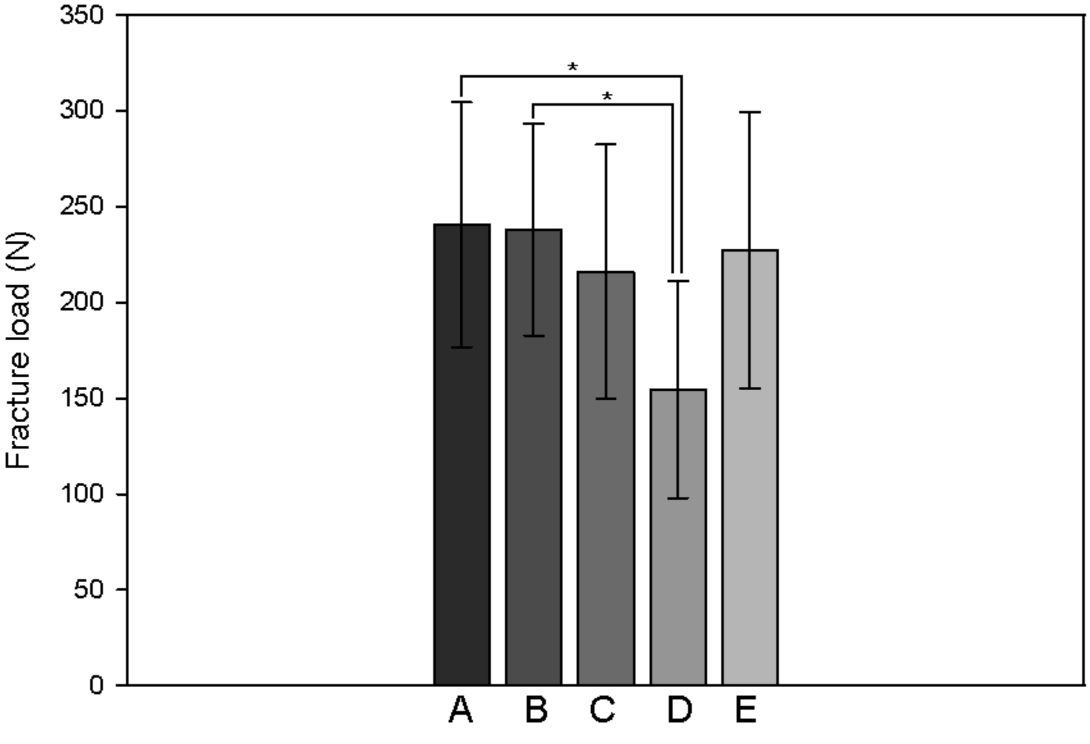

Figure 4.: Fracture loads in the different premolar study groups (mean ± SD). A: multiple elastic posts B: multiple regular FRC posts C: single elastic post D: single regular FRC post E: lateral condensation with elastic posts. * significant difference at the level p<0.05 (See also table 2).

	Restorable	Non-restorable
Multiple posts / elastic	7 (70%)	3 (30%)
Multiple posts / regular	7 (70%)	3 (30%)
Single post / elastic	7 (70%)	3 (30%)
Single post / regular	7 (70%)	3 (30%)
Lateral condensation / elastic	6 (60%)	4 (40%)

Table 5.: The distribution of fracture patterns among the premolar study groups.

Discussion

Dental fracture patterns depend on the direction and amount of force applied, and the ability of the tooth to recover from the deformation. Force may be relatively light and repetitive, as in normal mastication, relatively heavy and repetitive as seen in bruxism, and extremely heavy and sudden in cases of trauma [88]. The clinical applicability of the load range used in this study is confirmed by studies on the maximal bite forces in human. In the posterior region, forces range from 8 to 880 N during normal mastication, 597 N for women and 847 N for men on average [91]. Even greater loads have been described in bruxism, and teeth in this region may be exposed to extremely high forces when accidentally biting on a hard object (e.g. seeds, stone in salad, almond shell in cake) or in trauma. Such extreme forces cannot be completely absorbed, which leads to cracking and/or fracture of the enamel, but crack propagation towards the dentine is normally arrested by the DEJ. So far, this latter function of the DEJ has not been successfully mimicked by any restorative material, while, for instance, the high prevalence of temporomandibular disorders leading to bruxism in modern Western societies definitely points to such a need [92].

So far dental composites have been used most frequently to restore teeth with the direct method in the posterior region. Dental composites were introduced in the 1960s [93]. Since then several significant improvements have been made, but restorative composite resins still suffer from two key shortcomings: deficiencies of mechanical strength and high polymerization shrinkage [94].

These problems have been in the focus of intensive research, but a satisfactory solution has still not been found [24]. In 2013 a new, SFRC material was introduced to the market (EverX Posterior, GC Europe, Leuven, Belgium), intended to be a restorative material of enhanced durability for medium to large size class II cavities in the posterior region. During the premarket in vitro and clinical test phases, it showed better mechanical and polymerization stress properties than conventional composites, thus holding the promise of a new bio-mimetic restorative material for the posterior region, a part of the oral cavity where teeth are often exposed to excessive forces, leading to cracking and fracture [94-99].
In our study, the fracture toughness of teeth restored with different materials and restorative techniques was assessed. The applied techniques (i.e. incremental horizontal or oblique layering, the application of a stress-absorbing layer/ core, etc.) are all utilized to relieve the strain and stress generated in deep cavities [24], which is essential in the case of class II MOD cavities also [38, 100]. Flowable composite has been recommended as a stress- absorbing liner or base owing to its relatively low modulus of elasticity and greater ability to deform, thus contributing to a reduction of polymerization shrinkage stress from the overlying composite material [101]. Resin composites, if used with an incremental filling technique, are capable of reducing the concentration stresses at the tooth-restoration interface due to a reduction in the volume of the resin inserted. This leads to higher bond strengths than with the bulk technique [39]. While the issue of which incremental technique is most appropriate for clinical settings is a matter of controversy, the most widely accepted of these techniques is oblique layering, as this way the bonding together of opposing cusps is avoided, and stress levels are reduced [24].

In the first phase of the present study, the restoration of molars with horizontal layering of (conventional) composite resulted in significantly lower fracture toughness than controls (healthy molars). This finding is contrary to that of Park et al. [24] who showed that there was no significant difference between the horizontal and oblique layering of conventional composite in terms of stress generated by polymerization shrinkage and cuspal deflection. The application of SFRC is an attempt to mimic the DEJ and its biomechanical properties. In the present study, teeth restored with SFRC exhibited higher fracture toughness and load bearing capacity, regardless of the applied layering technique. Oblique layering yielded somewhat better results, but the difference, as compared to horizontal layering, was not statistically significant. This finding can be explained by the lower polymerization stress occurring at the restoration- bond interface in case of oblique layering [42]. Of all the restorative approaches tested, oblique layering of SFRC yielded the best results, in the sense that teeth restored this way exhibited fracture toughness closest to natural (i.e. intact controls). This finding may be explained by the low elastic modulus of the applied restorative material, which can enhance its crack blunting properties. It is known that materials with high elastic modulus tend to accumulate stresses, while low elastic modulus materials rather dissipate them [102]. Stress accumulation leads to crack development and propagation, while restorative materials that absorb and dissipate stress will protect the underlying structure. Stress dissipation is achieved due to the adequate size of the glass fibres in the SFRC material, namely 1 and 2 mm, thus exceeding the critical fibre length [103] and making stress transfer possible. It must be noted that such a good result was achieved only with oblique layering, which points out the superiority of this application technique over the horizontal one, even when restorative materials of advanced bio-mimetic properties are applied. The observations regarding the fracture patterns provide further support to the proposition that SFRC applied with an oblique technique yields better results than conventional composite applied with any technique or SFRC applied with a horizontal technique. Teeth restored with obliquely applied SFRC exhibited restorable fracture patterns in 62% of the cases, whereas the rest of the restorations performed at chance level or below it in this respect. This means that only obliquely applied SFRC could offer protection against unrestorable fractures above chance level (see Table 4.). This favourable outcome is possibly the result of the presence of glass fibres, which have been reported to act as stress breaker and stop crack propagation [104].

According to our results the use of SFRC yields favourable results in Class II cavities, which is important, as multi-surface restorations, extensive cavities, and Class II restorations, are more likely to fail than single-surface and Class I restorations [5]. One study calculated that Class II restorations have a relative failure risk of 2.8 compared to Class I restorations [2]. Another study demonstrated a failure risk increment of over 40% with every added restoration surface [105]. It is interesting to note that according to El-Helani et al. the preparation of an endodontic access after the preparation of an MOD cavity in the same tooth does not lead to further decrease in the fracture toughness, which indicates that the major factor in the decrease of fracture toughness is the preparation of the cavity itself [67]. Restoring non-vital teeth is a central issue in restorative and prosthetic dentistry [74, 106]. This is signified by the fact that endodontic posts for the restoration of such teeth appeared as early as in the 1800s. It is highly recommended that post insertion should not be carried out at the cost of sacrificing radicular dentine [107]. Studies have shown that post space preparation does not only weaken the tooth structure [108, 109], but it might also lead to cracks and defects that can concentrate stress and increase the chance of tooth fracture [110]. For these reasons, a minimally invasive post space preparation protocol was chosen for our study, and posts of the smallest available diameter (0.8 mm GC Fiber Post; 0.9 mm everStick POST) were selected. Goracci et al. showed that sliding friction was the main factor that affected resistance to dislocation of resin-bonded fibre posts [111]. This can be explained by the insufficient bonding to root canal dentine, which might be put down to several factors, such as the high c-factor, the increased thickness of the smear layer, poor moisture control in the root canal, etc. [112]. Sorensen et al. showed a significant increase in the fracture resistance of restored teeth when the posts were adapted closely to the canal walls [113]. The purpose of applying multiple posts in the same canal (multi-post techniques) or using a custom post is to achieve a better fit with the individual root canal anatomy. Through the use of a multi-post technique, it is possible to fill large and irregular root cavities more efficiently than with a single, centrally positioned post [85]. Also, with a multi-post technique, or by using a custom post, the amount of luting cement can be minimized [114], thus reducing the residual shrinkage of the cement and resulting in a better adaptation of the post.

The results of our study suggest the superiority of applying multiple posts in the same canal over a single one. Both multi-post techniques (rigid FRC (group 2.) and elastic FRC (group 4)) yielded significantly higher fracture resistance than the single post conventional FRC restoration (group 1). The findings also suggest that the elasticity of the post is not particularly important when applying a multi-post technique, since there was no statistical difference between the rigid and elastic multi-post techniques in terms of the fracture resistance of the restorations. It is interesting to note that neither of the two multi-post techniques yielded vastly different fracture resistance from the single elastic post technique. A possible explanation is that the elasticity (and thus better adaptability) of the particular type of elastic post used in this study was enough to make up for the disadvantages of using a single post only. However, the limitations of this investigation do not allow us to draw firm conclusions regarding this issue.

The rationale behind experimenting with custom post techniques in spite of the obvious advantages of the application of multiple posts is twofold: one of the reasons is that the problem of the insertion of a geometrically uniform and symmetric single FRC post into a root canal of irregularly varying diameter along its length is still not completely resolved. The other reason is that the amount of luting cement should be minimized, and the multi-post techniques, by nature, do not meet this requirement.

There are several methods to fabricate custom root canal posts [72, 87, 115, 116]. In our study the lateral condensation method of Hatta et al. [87] was used. The authors suggest that posts fabricated with this technique contain a higher volume of FRC, which, in turn, results in higher load-bearing capacity and thus a greater stability to the restoration. In the present study the individual posts (group 5) yielded better results than restoration with a single FRC post (groups 1 and 3). However, the difference did not reach the level of statistical significance. These results are in agreement with those of Hatta et al. [87] and Le Bell-Ronnlof et al. [117] in this respect. In our study the fracture resistances yielded by the individual post technique and the two multi-post techniques were not significantly different. The reason might be the minimal invasive preparation of the root canal, which can limit the number of posts insertable to approximately the same depth, thus making the cement-glass fibre ratio of the single post techniques similar to that of the multiple post techniques.

Fracture of the post(s) or the restored teeth themselves are among the most common failures of ETT restoration [118, 119]. While the use of metal posts leads more frequently to root fracture, the most common type of failure when FRC posts are used is debonding [120] or the fracture of the post [121, 122]. According to several studies, posts with an elastic modulus similar to that of dentine (i.e. fibre posts) can distribute stress more evenly along the post-dentine interface and thus prevent fractures more efficiently [123, 124]. The use of FRC posts may also result in a more favourable fracture pattern if fracture occurs [125-129]. This hypothesis is supported by both in vitro and clinical studies [119]. In the present study no difference was found between the study groups regarding the fracture pattern. As for that matter, the patterns out to be unusually uniform.

It is interesting to note that when a rigid FRC post was used, the failure usually occurred either at the post/core build-up interface with the core build-up detaching from the post, or the post fractured together with the core build-up. In contrast, when the elastic post was used the core build-up never detached from the post. This finding is in accordance with the results of Bell et al. who did not find adhesive (post-cement or post-core build-up) failure when testing this elastic post [81]. This can be explained by the structure of the tested posts. All FRC posts are made of two main components: fibres for reinforcement and a polymer matrix [120]. The matrix usually contains epoxy resins or other thermosetting polymers with a high degree of conversion and a highly cross-linked structure [130, 131]. Conventional (rigid) FRC posts are unable to form true chemical bonding with any composite material since the highly cross-linked polymer results in an inactive surface in these posts [81, 132, 133]. The elastic FRC posts contain a semi-interpenetrating polymer network (IPN) as the matrix component in which the fibres are embedded, and this network consists of both linear and cross-linked polymer phases. The linear phase in this material, polymethyl methacrylate (PMMA), can be dissolved if an adhesive resin is added on the surface of the post, leading to the formation of an interdiffusion zone at the interface. This zone is responsible for the formation of the actual chemical bonding between the post material and the composite material (in this case the core build-up).

This feature is both present in the SFRC material (EverX Posterior) and the elastic FRC post (everStick POST), leading us one step closer to true reinforcing bio-mimetic restorations.

In the second phase of our investigations, single-root upper premolars were tested because they have been shown to be more susceptible to root fractures when submitted to occlusal loading after endodontic treatment [84].

The tested premolar specimens received an oblique load (45 degree to the long axis of the tooth) which appears to be the worst case scenario in terms of the fracture resistance of ETT. Ambica et al. pointed out that the placement of a crown during endodontic restoration testing may obscure the effects of different build-up techniques [134]. Therefore, cores were not restored with crowns to exclude any external strengthening influence on the post and core foundations. This way the potentially confounding influence of the crown luting cement, and other unspecified factors influencing the performance of the final restoration were excluded. With all its limitations this method seems viable for the comparison of post and core build-up restorations. However, the lack of a crown might well be the very limitation because of which the results cannot be extrapolated to a clinical situation without further investigations. A further limitation of the premolar/post study might be the different size of the posts (0.8 GC Fiber Post and 0.9 everStick

POST), which makes direct comparison difficult. In-vitro tests with different post systems would also be desirable.

Conclusions

The studies described in this thesis sought to examine how FRC materials can be used in the most efficient way to reinforce the dental structure in both endodontically non-treated and root canal treated cases. Within the limitations of these in vitro investigations, it can be concluded that when restoring MOD cavities in endodontically non-treated molar teeth, the use of SFRC does not lead to a statistically significant increase in fracture toughness; however, there is a clear tendency towards higher fracture resistance and more favourable (restorable) fractures when using SFRC with an oblique layering technique. In the case of endodontically treated, single-root premolars restored in the absence of a ferrule, significantly higher fracture resistance is seen when a multi-post technique is used, as compared to utilising a single conventional FRC post. No statistically significant difference was found between using conventional or elastic FRC posts for multiple post restorations. Premolar teeth restored with a single elastic FRC post exhibited significantly higher fracture resistance than those restored with a single conventional FRC post. Fracture patterns were similarly favourable in all premolar groups. Finally, multi-post techniques are superior to single-post techniques in terms of achieved fracture resistance, regardless of the type of posts. In summary, it is recommendable that root canal treated premolar teeth be restored with multiple posts, but if for some reason a single post is chosen, this should be an elastic, fibre-reinforced one. As for the restoration of endodontically non-treated molars, the dentine should be substituted with SFRC for a more favourable fracture pattern, should fracture occur.

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Appendix:

Copies of the publications providing the basis of the thesis