UNIVERSITY of the WESTERN CAPE

Fracture resistance of endodontically treated maxillary premolars restored with horizontal glass fiber post: an *in vitro* and finite element analysis

A thesis submitted in fulfilment of the requirement for the degree of Doctor of Philosophy

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Keywords

- Endodontically treated teeth
- Maxillary premolars
- Fracture resistance
- Failure mode
- Horizontal glass fiber post
- Direct composite restoration
- MOD cavity
- Finite element analysis

Abstract

Introduction: Maxillary premolars are subjected to a combination of vertical and lateral occlusal forces. Furthermore, premolars present with an anatomical shape and unfavorable crown to root ratio, making them more prone to fractures than other posterior teeth. When endodontic treatment is combined with mesio-occluso-distal (MOD) cavities, the susceptibility to fracture increases.

Purpose: The purpose of this study was a) to determine the effect of the presence of a horizontal glass fiber post (HGFP) and the use of different root canal sealers on the fracture resistance, failure mode, and fracture patterns of MOD restored upper premolars; and b) to analyze the stress distribution when loading maxillary endodontically treated premolars (ETP) with restored MOD cavities with and without HGFP using 3-dimensional (3D) finite element analysis (FEA).

Methods: Sixty extracted intact human upper premolars received root canal treatment (RCT) and a MOD cavity preparation. Root canals were shaped using rotary files (ProTaper Next) up to apical size (X2) and were obturated with a matched single cone gutta-percha (GP). After that the teeth were divided randomly into 6 groups (n = 10) in accordance with the two study variables: the presence of HGFP and type of root canal sealer; Group1: AH Plus sealer, no HGFP; Group 2: TotalFill BC sealer, no HGFP; Group 3: BioRoot RCS sealer, no HGFP; Group 4: AH Plus sealer + HGFP; Group 5: TotalFill BC sealer + HGFP; Group 6: Bio Root RCS sealer + HGFP. The MOD cavities in all groups were restored using Filtek Z250 composite. All specimens were thermocycled (5^0C to 55^0C for 5000 cycles) and subjected to cyclic loading 50 000 times in a chewing simulator machine. Next, the specimens were subjected to axial loading using a universal testing machine until failure. A stereomicroscope was used to examine the fractured specimens to identify the fracture pattern. Fractures were classified as restorable or non-restorable. Data were analyzed using two-way ANOVA, one-way ANOVA, Chi-square, T-test, and Fisher exact test, with $\alpha = 0.05$.

Two micro-CTs of the same extracted upper premolar were produced, first a micro-CT of the tooth without the HGFP, followed by a micro-CT with the HGFP. The premolar was endodontically treated and restored following the same protocol as for the *in vitro* testing. These two micro-CTs were used to create two finite element (FE) models: one without HGFP and one with HGFP. Two loads, 200 N and 800 N were applied. Von

Mises stress distribution was evaluated for the two models by 3D finite element analysis (FEA) method.

Results: For the fracture resistance, the mean (standard deviation) failure loads for all groups were: G1: 827 (±296.87); G2: 764.88 (±285.98); G3: 758.40 (±294.37); G4: 879.70 (±236.62); G5: 911.33 (±325.59); G6: 1119.11 (±384.36). Two-way ANOVA revealed significant differences for the effect of HGFP (*P* = 0.029). The insertion of HGFP significantly increased the fracture resistance. The type of root canal sealer did not have an effect on fracture resistance (*P* = 0.561).

For the fracture patterns, the results revealed significant differences between the groups; HGFP group showed higher restorable fracture (78%) compared to groups without HGFP (44%) (*P* = 0.013). Finite element analysis showed that the inclusion of HGFP reduces the stress concentration at the occlusal interface and the cervical region under both loads.

Conclusion: A HGFP significantly increased the fracture resistance of endodontically treated upper premolars with MOD cavities and reduced the risk for non-restorable fractures. The FEA findings confirm the results of the *in vitro* testing. The type of root canal sealers did not affect the fracture resistance or fracture patterns of ETT.

Declaration

I hereby declare that "***Fracture resistance of endodontically treated maxillary premolars restored with horizontal glass fiber post: an in vitro and finite element analysis***" is my personal work, that it has not been submitted previously in its entirety or in part for any degree or examination at any other university, and that all the sources I have used or quoted have been indicated and acknowledged by a complete list of references.

Saleem Abdulrab

SIGNATURE **DATE:** 14 -4-2022

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Dedication

To those who give me everything for nothing to my dear wife, my parents, my beloved children, my brothers and sisters

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LIST OF ABBREVIATIONS

CR- Composite resin

CEJ- Cementoenamel junction

ETT- Endodontically treated tooth

ETP- Endodontically treated premolar

FRC- Fibre reinforced composite

FRC-post- Fibre reinforced composite post

FEA- Finite element analysis

GFP- Glass fiber post

GIC: Glass ionomer cement

GP- Gutta-percha

HGFP- Horizontal glass fiber post

mm- Millimetre

MOD- Mesio-occluso-distal

n- Number of specimens per group (group size)

N- Newtons

PDL- Periodontal ligament

PDF- Fixed partial denture

PEF: Polyethylene fiber

RBC – Resin-based composite

RCT- Root canal treatment

SD- Standard Deviation

VRF- Vertical root fracture

CHAPTER 1: LITERATURE REVIEW

1.1 Introduction

Endodontically treated teeth (ETT) are more prone to fracture because of their weakened structure. Root canal therapy procedures, including access cavity preparation, root canal shaping, disinfection, and obturation, are considered probable predisposing factors (Trope and Ray, 1992; Uzunoglu *et al.*, 2012). Also, severe damage to a tooth's coronal structure due to decay or traumatic dental injury commonly necessitates placing a post system inside the root canal following endodontic treatment to support and retain a core and coronal restorations (Goracci and Ferrari, 2011), further compromising the structural integrity of the tooth.

In restorative dentistry, the clinical decision of how to restore ETT with substantial coronal damage is a challenge (Scotti *et al.*, 2016). When a post is deemed necessary to rebuild and retain a coronal restoration, clinicians increasingly opt for fiber post materials with biomechanical features similar to dentin. This provides inhomogeneous stress distributions and minimizes the risk of catastrophic root fractures (Hatta *et al.*, 2011; Kim *et al.*, 2016).

Endodontically treated premolars (ETP) have the lowest survival rates because of the high incidence of vertical root fracture (Khasnis *et al.*, 2014; Yoshino *et al.*, 2015; Almasri, 2019). This fragility is explained by the relatively small size of their crown and the high occlusal forces they are subjected to (van Reenen and Reid, 1996; Raiden *et al.*, 1999). Besides root fractures, cusp fractures often occur in premolars because of the anatomical shape, unfavorable crown to root ratio, and exposure to vertical and lateral occlusal forces (Shafiei *et al.*, 2014). Structural integrity may be further compromised when root canal treatment (RCT) is accompanied with mesio-occluso-distal (MOD) cavities. It has been shown that tooth stiffness decreases by 46% when only one marginal ridge is lost and 63 % when the two marginal ridges are lost (Reeh *et al.*, 1989b). The prognosis of ETP is affected by different parameters such as the coronal residual tooth structure (Bitter *et al.*, 2009), cavity preparation depth and design (Liu *et al.*, 2014; Alshiddi and Aljinbaz, 2016), the existence of a minimum of 1.5–2.0 mm ferrule height (Samran *et al.*, 2013), post and core material used (Sidoli *et al.*, 1997), and the marginal seal of restoration (Ferrari *et al.*, 2022).

Endodontic obturation is traditionally done using GP combined with a sealer to provide a total 3-D filling of the root canal space (Schilder, 1967). The long-term success of an ETT may be enhanced if an optimal root canal obturation material bonds to the root canal dentin and strengthens the residual tooth structure against fracture. (Johnson *et al.*, 2000). Due to the inability of GP to adhere to the walls of the root canals, root canal sealers could have a significant influence in this situation. (Sağsen *et al.*, 2012). A recent systematic review found that most studies, included in the review, reported that the use of root canal sealers, except zinc oxide eugenol-based sealers, increased fracture resistance of ETT (Uzunoglu-Özyürek *et al.*, 2018). Recently, sealers based on calcium silicates (bioceramic) have been widely used due to their favorable biological properties. They are biocompatible and non-cytotoxic, are dimensionally stable, chemically bond to root dentin, promote an alkaline pH, have antimicrobial properties, and contribute to enhanced root strength after obturation (Wang, 2015; Al-Haddad and Che Ab Aziz, 2016; Poggio *et al.*, 2017).

Finite element analysis (FEA) is an engineering method that depends on computer-based numerical analysis in order to assess complex structures utilizing their mechanical properties with an ultimate aim to determine the distribution of stress upon force application. It is a valuable and reliable method in simulating and evaluating the different mechanical aspects of biomaterials and human tissue that can be difficult to measure in vivo. FEA has been employed in many studies aiming to investigate the stress distribution in ETT, restored with different post and core techniques; the results showed that fiber posts resulted in a decreased stress concentration at the post end because their elastic modulus is similar to that of dentin (Coelho *et al.*, 2009; Ona *et al.*, 2013).

Full-coverage restoration of an ETT is considered an invasive and irreversible intervention. It is often an indirect procedure involving the services of a dental technical laboratory, implying additional costs and visits for the patient. A horizontal fiber post placement is a direct and less invasive procedure than an indirect full-coverage restoration. There is no need to involve a dental technical laboratory, hence saving costs for the patient and reducing the number of visits to the dentist.

Many studies have investigated the effects of HGFP on the fracture resistance of ETP. It was published that the use of HGFPs in MOD cavities restored with composite resin

(CR) improved the fracture resistance of ETP (Karzoun *et al.*, 2015; Bromberg *et al.*, 2016) and decreased unrestorable catastrophic fractures (Mergulhão *et al.*, 2019). However, no studies have been reported on the effect of different types of sealers in combination with HGFP on the fracture resistance of ETTsubjected to thermocycling and dynamic loading. Furthermore, no studies are reported that assess the impact of using horizontal glass HGFP using FEA. The process of fatiguing is important in the in vitro analysis of failure of complex systems that need to function for prolonged periods in the mouth. Different materials and interfaces in the complex structure may degrade at different rates during function in the mouth, which may not be simulated by means of static tests. Finite element analysis is an important instrument to better understand and explain failure patterns of restorations (Ordinola-Zapata et al., 2022). Therefore, this study aimed to evaluate the impact of the inclusion of a HGFP and different types of sealers on the fracture resistance and fracture pattern of ETP by *in vitro* work and numerical simulations using FEA.

1.2 Restoration of endodontically treated teeth

An ETT is a tooth that has received RCT to manage acute or chronic pulpitis resulting from dental caries and/or trauma. Successful RCT starts with complete canal cleaning and shaping, followed by disinfection of the pulp system, and is completed with root canal obturation. ETT is more susceptible to fracture than vital teeth because of dentin dehydration and hard tissue loss (Reeh *et al.*, 1989b). This hard tissue loss can occur due to caries, trauma, or pre-existing restorations (Sedgley and Messer, 1992).

1.2.1 Direct versus indirect restoration of endodontically treated teeth

A Cochrane review comparing single crowns and direct restorations for the restoration of ETP found that there was inadequate evidence to decide whether direct restorations or crowns should be preferred for the restoration of ETP (Sequeira-Byron *et al.,* 2015). A randomized clinical trial in ETT (anterior, premolars, and molars) with extensive coronal damage found no significant difference in the survival of crowns and composites. The researchers concluded that CR restorations and porcelain-fused-to-metal crowns could improve survival and success rates (Skupien *et al.*, 2016). Another systematic review suggested that CR restoration and crowns did not have significantly different longevity in ETT (premolars and molars) with minimal to moderate tooth structural loss (Suksaphar *et al.*, 2017).

According to retrospective cohort research, ETT (premolars and molars) with coronal defects absent up to three surfaces could be restored using an adhesive composite restoration. The study also found that full-coverage crowns had a 95.2 % 10-year survival rate while CR restorations had a 91.9 % survival rate (Dammaschke *et al.*, 2013).

A recent retrospective study indicated that posterior teeth (premolar and molar) restored with class II composite restorations with 2.5- to 3-mm cusp thickness in ETT versus vital teeth had similar long-term durability of 6 to 13 years (Lempel *et al.*, 2019). Furthermore, a 5-year retrospective study concluded that when ETT (premolars and molars) was restored with crowns, the survival rate was much greater than when it was restored with CR; However, the survival rate of ETT with one or two surface losses and two adjacent teeth was not significantly different. ETT restored with CR had mostly restorable fractures, whereas those with crowns were unrestorable (Jirathanyanatt *et al.*, 2019).

In a meta-analysis of direct and indirect ETT (anterior, premolar, molar) restoration outcomes found no differences in five-year outcomes between direct and indirect restorations. However, superior outcomes showed with indirect restoration at ten years (Shu *et al.*, 2018).

A recently published systematic review and meta-analysis by de Kuijper *et al.* (2021) analyzed the available literature on the direct and indirect restoration of endodontically treated posterior teeth. They concluded that low-quality evidence shows no difference in tooth survival for the short term (2.5 to 3 years).

Based on the current evidence, it can be concluded that for the short term, there is no difference between direct and indirect restoration for ETT (premolar, molar), especially with minimum to moderate loss of tooth structure. However, there is a weak recommendation for indirect restorations, especially for teeth with extensive coronal damage.

1.2.2 Direct restorative materials: resin composite

Resin composites are mainly composed of three phases, each contributing to material properties; a. resin matrix: Bisphenol A diglycidyl ether dimethacrylate (BisGMA) and Urethane dimethacrylate (UDMA) monomers, b. fillers: silica fillers and c. filler-resin interface: a silane-coupling agent (Anderson *et al.*, 2013). The resin phase is composed of polymerizable monomers. These monomers transform from a liquid stage to a highly cross-linked polymer stage upon exposure to visible light. Fillers types and contents volume determine the mechanical properties of CR materials and allow reducing the monomer content and the polymerization shrinkage (Ilie *et al.*, 2013). They also help optimise wear, translucency, radiopacity, surface roughness, and polishability and enhance aesthetics and improve handling properties. Finally, the filler-resin interface allows the coupling of the polymerizable matrix to the filler particles (Ástvaldsdóttir *et al.*, 2015).

In order to improve the strength of the composite, the size of filler particles was reduced from macro to micro fillers, where the size of particles was just a few micrometres (0.01 μm-0.05 μm). The microfilled composites had better polishability, but the filler's small volume and high surface area made it difficult to obtain high filler loads, leading to decreased physical properties (Leprince *et al.*, 2014). To increase the filler content, highly filled pre-polymerized resin fillers were impregnated within the matrix of microfilled materials forming hybrid materials and thus combining macrofilled and microfilled CR together (Coelho-de-Souza *et al.*, 2015).

Furthermore, more modifications were done in the particle size through the power of milling and grinding techniques resulting in resin particles about approximately 0.4-1.0 μm, called minifills. Addition of these particles to resin matrix of microfilled composites formed the term of microhybrid composite resin, aiming to obtain more advantages with the strength of composite materials and increasing the filler loading, which decreases the polymerization shrinkage stresses (Baroudi and Rodrigues, 2015).

1.2.2.1 Nanohybride composite

Nanotechnology has recently been introduced into CR materials, such as nanofilled and nanohybrid resin composites. Nanofilled composites contain nanosized particles through the resin matrix, whereas nanohybrids use a combination of nanosized and traditional filler particles. The most common are nanohybrid resin composites, which combine nanoparticles with submicron particles to optimize the distribution of fillers in the matrix, resulting in better mechanical, chemical, and optical properties (Saen *et al.*, 2016; Wang *et al.*, 2018).

Using nanotechnology, the filler particle size went down to nano scale, leading to the development of approximately 5-40 nm filler particles. Most manufacturers nowadays did alternation in the formulations of their microhybrid to include more nanofilllers producing nanohybrid composites. As a result of the reduced particle size, increased filler load can be achieved, reducing polymerization shrinkage and improving mechanical and optical properties. The properties of these composites seem to be equal or sometimes greater than microhybrid composites. Thus, nanohybrid composites are marketed as universal composites that can be used in both anterior and posterior region (Miletic, 2018).

The Academy of Operative Dentistry - European section (AODES) recommends using microhybrid or nanohybrid CR with a minimum 60% filler load by volume (Campos *et al.*, 2014). Fillers are responsible for most of the mechanical properties of the CR. Increasing the filler loading improves wear resistance to increased functional loading and reduces polymerization shrinkage. Many follow-up studies have shown that nanohybrid and conventional hybrid composite materials have comparable clinical durability (van Dijken and Pallesen, 2013; van Dijken and Pallesen, 2014). Some studies have documented that filler size and filler load affect the failure mode (Sabbagh *et al.*, 2017).

1.2.3 Posts

Post and core restorations are used to restore ETT with extensive loss of coronal tooth structure. The post is inserted in the canal to provide retention and anchorage for the core restoration when adequate coronal tooth structure is unavailable to support the core (Schwartz and Robbins, 2004), followed by a full crown or fixed partial denture.

An ideal post should preserve tooth structure and dissipate occlusal forces in a strategic pattern within the radicular dentin to avoid tooth fracture (Asmussen *et al.*, 1999). The efficiency of posts is affected by post length, diameter, design, surface configuration, and material (metallic or non-metallic) factors.

Assessment of the teeth' structural, mechanical, and functional properties has led to the development of restorative systems that mimic natural tooth structures. In this context, non-metallic posts, namely fiber reinforced composite (FRC) posts, were introduced and perceived by clinicians as an alternative post material to the traditional metallic predecessor. Fiber reinforced composite posts are composite resin intra-radicular posts characterized by improved mechanical, aesthetic, and bonding properties. Different glass FRC post systems have been introduced: prefabricated FRC posts, individually-formed FRC posts, and short-FRC (SFRC) posts.

1.2.3.1 Prefabricated glass FRC post

The concept of incorporating reinforcing fiber into a resin matrix to produce intra-radicular post has been demonstrated primarily in the prefabricated FRC posts. The prefabricated FRC post consists of a high volume fraction of closely packed long continuous unidirectional fibres embedded in a fully-polymerized (cross-linked) epoxy resin matrix or a combination of epoxy and dimethacrylate resins (Lamichhane *et al.*, 2014). A wide variety of prefabricated glass FRC posts manufactured in several compositions, designs, dimensions, translucencies, and therefore variable mechanical and physical properties, have become available. Now, glass FRC post are the most commonly used to reinforce composites in the dental field. Glass fibres have high mechanical strength, low cost, transparent aesthetic appearance, and most importantly, the modulus of elasticity similar to dentin. Prefabricated glass FRC posts are cemented to the canal using CR luting cement. Subsequently, a core is constructed using a variety of CR materials. It has been suggested that adhesively bonded post (using resin cements) together with a CR core, creates a homogenous unit, which might further contribute to the homogeneity of stresses distribution in ETT (Mendoza *et al.*, 1997; Mezzomo *et al.*, 2003).

When compared to metallic posts, prefabricated glass FRC posts are biologically, mechanically, and aesthetically compatible with tooth structure. Prefabricated glass fibre posts have been primarily promoted for their modulus of elasticity that is compatible with dentine when compared to metallic posts. This compatibility has been reported to allow slight post flexion during function, which presumably dissipates stresses and reduces unfavourable tooth failure's likelihood (Fokkinga *et al.*, 2004; Galhano *et al.*, 2005).

One of the shortcomings of the prefabricated FRC posts is the fact that they are manufactured to a predetermined shape and diameter that rarely adapt well to the root canal anatomy. Therefore, they are centrally positioned in the neutral axis of the canal.

1.2.3.2 Fiber post versus metal post

Reports on the fracture resistance of ETT restored with prefabricated glass FRC posts compared to metal posts were inconclusive. Higher failure load has been reported in both metal posts (Newman *et al.*, 2003; McLaren *et al.*, 2009) and in FRC posts (Barjau-Escribano *et al.*, 2006; Hayashi *et al.*, 2006), while other reports have found no significant difference in failure loads between metal and FRC posts (Hu *et al.*, 2003; Fokkinga *et al.*, 2006). Fokkinga *et al.* (2004) conducted a review and reported that ETT restored with prefabricated glass FRC posts have more restorable failures when compared with metal posts. A systematic review with meta-analysis of (Zhou and Wang, 2013) found that cast posts had higher fracture strength than glass fiber post (GFP), but fiber post resulted in more favourable fractures. However, a systematic review and meta-analysis of clinical studies did not find a difference among the types of posts (metal vs fiber) regarding survival rate, and ratios of restorable or non-restorable failure of RCT teeth (Figueiredo *et al.*, 2015). Numerous studies included in this meta-analysis showed high risk of bias and heterogeneity, which weakens the concluded evidence. In 2017, another systematic review of ETT failure modes found that metal posts have a higher risk of root fracture than glass-fiber posts. Glass-fiber posts have a higher risk of post, crown, and core failure. In conclusion, metal and fiber posts have the same clinical performance at short and medium-term follow-up. (Marchionatti *et al.*, 2017). A recent systematic review and meta-analysis (Wang *et al.*, 2019) concluded that fiber posts demonstrated higher medium-term survival rates (3 to 7 years) than metal posts when used to restore ETT with two coronal walls remaining or less.

In a randomized controlled trial, compared GFP survival and success rate to cast metal post in teeth without ferrule. Glass fiber and cast metal posts performed similarly clinically after nine years of follow-up (Sarkis-Onofre *et al.*, 2020).

In a recent systematic review and meta-analysis assessed the evidence about the failure rates of ETT restored with intraradicular metal posts or fiber posts. They concluded that no difference was observed between fiber and metal post-failure rates (Martins *et al.*, 2021).

1.2.3.3 Post versus no post

Concerning placement of a post or not, a systematic review recommends ETT molars and premolars that have lost less than 50% of their coronal structure can be restored without the need for posts, especially when cusp protection is planned (Aurélio *et al.*, 2016). Another systematic review found that post-placement would be useful for the failure mode and success rate of ETT (Zhu *et al.*, 2015). Naumann *et al.* (2018) conducted a systematic review of the effect of post-placement on the clinical performance of restored ETT. They concluded that there is no conclusive clinical evidence either in favor of or against the use of posts in no-wall cavities for either direct or indirect restorations. Furthermore, Zarow *et al.* (2018) suggested using fiber posts in anterior teeth and premolars with severely damaged tooth structure <50%. Thus, current literature does not support using a post to restore ETT based on *in vitro* and clinical research as well as a systematic review (Brignardello-Petersen, 2018).

In a recent systematic review and meta-analysis performed to determine whether the presence of an intraradicular post increased the fracture strength of ETP directly restored with composite, Iaculli *et al.* (2021) concluded that ETP restored with a fiber post and direct CR restoration had higher fracture resistance than ETP without a post.

1.2.4 Effect of different dentin substitute materials on fracture resistance/fracture pattern of MOD endodontically treated premolars teeth (biomechanical behaviour of the tooth-restoration complex)

The use of restorative materials with mechanical properties similar to the dental structure and maximize healthy tooth preservation may influence the behaviour and fracture pattern as well as provide greater longevity of the tooth-restoration complex under test conditions (Burke, 1992; Magne and Belser, 2003; Soares *et al.*, 2004; Soares *et al.*, 2008c). In this context, endodontic therapy removes internal tooth structure, making ETT more prone to fracture than sound teeth.

Ausiello *et al.* (1997) investigated adhesion of various materials to ETT cusp fracture resistance, extracted healthy maxillary premolars were treated using MOD preparations and endodontics. The amalgam Valiant was used in conjunction with Superbond or

Panavia bonding to restore the cavities. The resin composites Z100, Herculite XRV, and Clearfil RP were used in conjunction with their respective bonding systems. Z100 was also used with the glass ionomers Ketac Fil, Fuji II, and Vitremer, while Tetric was used in conjunction with Compoglass. They found that adhesive resin composite restorations increase the fracture resistance of ETT compared to non-adhesive fillings.

Soares *et al.* (2008c) assessed the fracture strength of ETP restored with different materials. Seven groups of ten maxillary premolars were chosen. The control group had healthy unprepared teeth. The other six groups had endodontic treatment with one of two cavity preparation designs: direct MOD; indirect MOD. The following materials were used to restore teeth: amalgam, CR, LAB-processed CR and leucite-reinforced glass-ceramic. Results found that direct CR restorations, laboratory-processed CR, and ceramic restorations significantly improved the fracture resistance of ETP with MOD cavity preparations.

Soares *et al.* (2008d) evaluated the effect of RCT and restoration on the fracture resistance of MOD cavities upper premolars. Fifty sound premolars were chosen and divided into five groups: Group1, control teeth; Group2, MOD cavity; Group 3, MOD cavity restored with CR (Z-250, 3M ESPE); Group 4, MOD cavity and RCT; and Group 5, MOD cavity, RCT, and CR restoration. It was concluded that CR restoration plays an important role in reinforcing the remaining dental structure. However, restoration and RCT increased the incidence of unfavourable failure mode.

Taha *et al.* (2011) compared CR restoration and variable cavity design on fracture resistance of ETP. Eighty sound teeth were used with three types of access cavity design: with no axial wall, extensive, and conventional. It was found that direct restorations improved fracture strength of ETT with extensive endodontic access. Similar patterns of fracture in both restored and unrestored teeth.

Taha *et al.* (2014) assessed fracture resistance and fracture patterns of ETP with MOD direct CR restorations under static and cyclic loading. Forty-eight maxillary premolars were endodontically treated and divided into three groups: 1) CR; 2) GIC core and CR; and 3) open laminate technique with GIC and CR. They found that CR restorations had significantly improved fracture resistance than other restorations. Dynamically loaded teeth failed at a lower load than did non-cycled teeth. Therefore, it negatively influenced the fracture resistance of restored teeth.

Atiyah and Baban (2014) evaluated the fracture strength of ETP with MOD cavities restored with three different CR restorations. They found that composite restorations showed significantly improved cuspal fracture resistance compared to unrestored ones. Regarding fracture pattern, the sound teeth group showed a more favourable fracture, whereas other groups showed more unfavourable fracture.

Sarabi *et al.* (2015) evaluated fracture strength, failure mode, and fracture location of ETP restored with direct and indirect CR and ceramic restoration. Eighty upper premolars were divided into four groups. There were RCT and MOD preparations in all of the groups. They found direct CR increased fracture resistance; however, failure modes may be unfavourable.

Toz *et al.* (2015) evaluated the effect of different type of bulk-fill flowable composites on fracture strength of ETT with MOD cavities. RCT was performed on forty-two upper premolars. Teeth were divided into six groups according to restorative materials. Results showed, in terms of fracture resistance, there were no statistically significant differences between groups.

Atalay *et al.* (2016) compared the effect of different types of restorative resins on fracture strength of ETT with MOD cavities. According to restorative materials, seventy-two sound upper premolar teeth were divided into six groups. According to their findings, ETT restored with bulk-fill/bulk-fill flowable or fiber-reinforced composite had similar fracture strengths as ETT restored with conventional nanohybrid CR.

Taha *et al.* (2017) evaluated the influence of using a bulk-fill flowable base material on fracture resistance and fracture patterns of upper ETP with MOD cavities. Fifty extracted upper premolars were divided into five groups. The results showed that the fracture resistance of ETP with MOD cavities was significantly improved by using a bulk-fill flowable base material; however, the fracture patterns were not improved to more favourable ones.

Göktürk *et al.* (2018) investigated the fracture resistance of ETP with MOD cavities restored by different restorations. Fifty-five intact upper premolar teeth were selected. Results concluded that all of the restoration techniques improved the fracture resistance of teeth; however, their values were lower than intact teeth. The fracture resistance values of the groups with different restorations did not differ significantly.

Bajunaid *et al.* (2020) compared the fracture strength of ETP by using three restorative materials (i.e., direct composite (Filtek Z250), indirect composite inlays (Filtek Z250), and CAD/CAM ceramic inlays to restore MOD preparation. The results showed that direct CR showed the highest fracture resistance. There was no statistical difference in fracture mode amongst all groups.

Based on the above studies, it can be concluded that direct resin composite significantly improved the fracture resistance of ETP with MOD cavities. In addition, no significant difference according to the type of composite, either conventional or bulk fill. However, most studies reported unfavourable fractures patterns. Therefore, direct CR did not improve fracture patterns to more favourable ones.

Table 1.1. provides a summary of the previous studies' outcomes on the effect of different dentin substitute materials on fracture resistance/fracture pattern of MOD endodontically treated premolars teeth.

Table 1.1: Summary of the effect of different dentin substitute materials on fracture resistance/fracture pattern of MOD endodontically treated premolars teeth.								
Reference	In vitro / in vivo	Type of teeth	Damage to tooth (number of walls standing)	Endo post yes/no	Horizontal post yes/no	Type of restoration (direct, indirect, onlay, inlay, crown)	Outcomes (fracture e patterns, failure mode)	Results (significant / not sign)
Ausiello *et al.*, 1997	In vitro	Upper Premolar	2 walls	No	No	1-Amalgam 2-Resin composite 3-Glass ionomers Ketac Fil 4-Tetric in combination with Compoglass	Fracture resistance	CR increases the fracture resistance significantly of root-filled teeth compared to non-adhesive fillings.
Soares et al., 2008	In vitro	Upper Premolar	2 walls	No	No	1-Amalgam 2-CR 3- laboratory-processed CR 4- leucite-reinforced glass-ceramic	-Fracture resistance - Fracture mode	- All types of restoration except amalgam improved the FR significantly. - leucite-reinforced glass-ceramic showed the less catastrophic fracture
Soares et al., 2008d	In vitro	Upper Premolar	2 walls	No	No	1-MOD+CR 2-MOD+RCT+CR	-Fracture resistance - Fracture mode	Fracture resistance of MOD with CR significantly higher than MOD+RCT+CR Both groups exhibits high non-restorable fracture
Taha *et al.*, 2011)	In vitro	Upper Premolar	2 walls	No	No	1-MOD+CR 2-MOD+RCT+CR 3-MOD+RCT+GIC core and CR	-Fracture resistance - Fracture mode	Direct composite restoration significantly increased fracture resistance of ETT. Both restored and unrestored teeth showed similar fracture patterns.
Taha et al., 2014	In vitro	Upper Premolar	2 walls	No	No	1-CR 2- GIC+CR 3- Open laminate technique with GIC and RC	-Fracture strength -Fracture patterns	CR restoration had significantly higher fracture strength than other restorations
Atiyah and Baban, 2014	In vitro	Upper Premolar	2 walls	No	No	1-Filtek Z250 XT 2-SDR bulk-fill flowable composite 3-Filtek P90 composite	-Fracture resistance -fracture pattern	CR showed significant improvement in the cuspal fracture resistance compared to unrestored one. However, presented unfavorable fracture type
Sarabi *et al.*, 2015	In vitro	Upper Premolar	2 walls	N0	No	1- Indirect composite restoration 2- Ceramic restoration 3- Direct composite restoration	-Fracture resistance - failure mode	Direct composite restorations resulted in higher resistance against fracture, but their failure modes may be unfavorable.

Toz *et al.*, 2015	In vitro	Upper Premolar	2 walls	No	No	1: Clearfil Majesty Flow and Clearfil Majesty Posterior 2: Venus Bulk Fill and Clearfil Majesty Posterior 3: Clearfil Majesty Posterior 4: Vertise Flow and Clearfil Majesty Posterior 5: SDR and Clearfil Majesty Posterior 6: X-tra base and Clearfil Majesty Posterior	-Fracture resistance	No statistically significant differences between groups in fracture strength
Atalay *et al.*, 2016	In vitro	Upper Premolar	2 walls	No	No	1: Bulk fill resin composite/Filtek Bulk Fill 2: Bulk fill flowable resin composite + nanohybrid/SureFil SDR Flow + Ceram.X Mono 3: Fiber-reinforced composite + posterior resin composite/GC everX posterior+ G-aenial posterior 4: Nanohybrid resin composite/Tetric N-Ceram	Fracture resistance	No statistically significant differences between bulk fill/bulk fill flowable or fiber-reinforced composite and conventional nonhybrid CR
Taha *et al.*, 2017	In vitro	Upper Premolar	2 walls	No	No	1: Vitrebond base and resin-based composite 2: GIC base (Fuji IX GP) and CR 3: Bulk-fill flowable base material (SDR) and CR	-Fracture resistance -Fracture pattern	Using a bulk-fill flowable base material significantly improved the fracture strength of ETP with MOD cavities; however, it did not improve fracture patterns to more favourable ones.
Göktürk *et al.*, 2018	In vitro	Upper Premolar	2 walls	No	No	1: Direct composite restoration 2: Direct composite strengthened with buccal to lingual pre-impregnated glass-fibers 3: Ceramic inlay restoration	-Fracture resistance	All tested materials increased the fracture strength of teeth. But, no significant differences between the groups

Bajunaid *et al.*, 2020	In vitro	Upper Premolar	3 walls MO cavity	No	No	1: Direct Filtek Z250 composite 2: indirect inlay Filtek Z250 composite 3: IPS E.Max CAD/CAM monolithic ceramic inlays	-Fracture resistance - Fracture mode	Direct composite restorations showed the highest fracture resistance, followed by CAD/CAM ceramic restorations and indirect composite restorations. All groups show no significant difference was observed in the fracture mode

1.2.5 Effect of intraradicular fiber post on fracture resistance/ fracture pattern of MOD endodontically treated maxillary premolars

Several studies have suggested that RCT upper premolars without a fiber post have fracture resistance comparable to those restored with a fiber post (Krejci *et al.*, 2003; Fokkinga *et al.*, 2005; Siso *et al.*, 2007), In contrast, other studies showed improved fracture resistance when a conventional fiber post was used compared to a CR alone (Nam *et al.*, 2010; Scotti *et al.*, 2015). It has been demonstrated that ETP with MO cavities could not be strengthened with a CR alone because the fracture strength of these teeth is lower than that of intact teeth (Nothdurft *et al.*, 2008; Shah *et al.*, 2020; Fráter *et al.*, 2021).

Soares *et al.* (2008a) evaluated whether the fracture resistance was influenced by cavity design and GFP of ETP restored with CR. They found that GFP did not strengthen the ETP.

Mohammadi *et al.* (2009) evaluated the influence of fiber post and cusp coverage on fracture resistance of ETP directly restored with CR. Seventy-five upper premolars were divided into 5 groups. There was a reduction in buccal and lingual cusps up to 2 mm in the cusp covering groups. The authors concluded that ETP with MOD preparations restored with direct CR had comparable fracture resistance whether or not fiber post and cusp capping were used.

Scotti *et al.* (2011) assessed the effect of the fiber post, post length, and/or cuspal coverage on ETP fracture resistance. Seventy sound upper premolars were distributed into seven groups: "intact teeth" (control), "inlay without fiber post" (G1), "inlay with long fiber post" (G2), "inlay with short fiber post" (G3), "onlay without fiber post" (G4), "onlay with long fiber post" (G5), and "onlay with short fiber post" (G6). All specimens were thermocycled, subjected to cyclic loading, and then subjected to the static fracture test. Comparable fracture resistance was found for ETP with MOD cavity restored by direct CR with fiber post or cusp capping.

Al-Makramani *et al.* (2013) evaluated the influence of restorative materials and GFP on the fracture strength of ETP. Fifty extracted mandibular premolars and distributed into 5 groups: intact control group; MOD cavity + RCT + CR; MOD cavity + RCT + GFP + CR; MOD cavity + RCT + amalgam restoration; MOD cavity + RCT + GFP +

amalgam restoration. The results revealed no significant difference between groups with and without GFP.

Scotti *et al.* (2015) compared the longevity of ETT restored with direct CR without cusp coverage and with or without fiber posts. A total of 247 patients with 376 root-treated posterior teeth were recalled for a control visit. The fiber post was absent in G1 and present in G2. Periodontal and endodontic failures, tooth extraction, root fracture, post debonding, crown displacement, restoration replacement were recorded. They found that direct restorations with fiber posts were significantly better than restorations without posts after three years of clinical function.

Lin *et al.* (2018) compared the fracture resistance, fracture pattern, types of fracture among ETP restored with different restorative materials. It was concluded that fiber post and composite core restorations outperformed Nayyar's core amalgam restorations in fracture resistance. Most coronal fractures were considered a favourable pattern.

da Rocha *et al.* (2019) evaluated the effect of the restorative materials on the mechanical response of upper ETP with MOD cavities. Forty-eight upper premolars received MOD cavities with different restorative techniques: glass ionomer cement + CR, a metallic post + CR, a fiberglass post + CR, or no RCT + restoration with CR. They found Interradicular posts for ETP with MOD restoration have no mechanical benefit.

Mena-Álvarez *et al.* (2020) investigated the fracture strength of upper ETP restored with GFP, glass fiber elastic posts, conventional CR, and FRC resins. Seventy premolars with different restorative techniques. It was concluded that elastic FRC post enhances the fracture resistance of upper ETP teeth compared to FRC post and only CR core.

Spicciarelli *et al.* (2020) assessed the fracture strength and failure pattern of upper ETP with several coronal walls missing and post-endodontic restoration. One hundred five premolars were distributed into 3 groups based on the remaining walls. The results showed that the double-post approach did not increase the fracture resistance of extensive damaged upper ETP with two roots. The group without post showed more unrestorable fractures.

The vast majority of the above studies (6) indicate that ETP without a fiber post shows similar fracture resistance to those restored with an intra radicular post. However, a few studies (2) showed improved fracture resistance when a fiber post was used compared to a composite filling alone. However, more favourable fracture pattern reported with fiber post. Therefore, the present studies are was still inconclusive to support the use of intra radicular fiber post to reinforce ETP.

Table 1.2 summarizes the previous studies' findings on the effect of the use of intraradicular fiber post on fracture resistance / pattern of ETP with MODs

Table 1.2: The effect of the use of intraradicular fiber post on fracture resistance / pattern of ETP with MOD

Reference	In vitro / in vivo	Type of teeth	Damage to tooth (number of walls standing)	Endo post yes/no	Horizontal post yes / no	Type of restoration (direct, indirect, onlay, inlay, crown)	Outcomes (fracture patterns, failure mode)	Results (significant / not sign)
Soares *et al.*, 2008a	In vitro	Upper Premolar	2 walls	Yes	No	1:MOD+RCT+CR 2:MOD+RCT+GFP+CR	-Fracture resistance -Failure modes	the use of GFP did not reinforce the ETT significantly. The combination of the fiber post with an adhesive restoration showed more favorable failure types.
Mohammadi *et al.*, 2009	In vitro	Upper Premolar	2 walls	Yes	No	1: CR without GFP and cusp capping. 2: CR without GFP but with cusp capping. 3: CR with GFP but without cusp capping. 4: CR with GFP and cusp capping.	-Fracture resistance -Failure modes	There were no significant differences in fracture resistance between the groups; direct CR, with or without GFP and cusp capping had comparable fracture resistance. Most of the fractures were unfavorable in the groups.
Scotti *et al.*, 2011	In vitro	Upper Premolar	2 walls	Yes	No	1: inlay without fiber post 2: inlay with long fiber post 3: inlay with short fiber post 4: onlay without fiber post 5: onlay with long fiber post 6: onlay with short fiber post	-Fracture resistance - Fracture mode	No statistically significant among groups. (Similar fracture resistance) the combination of the fiber post with an inlay adhesive restoration led to more favorable failure.
Al-Makramani *et al.*, 2013	In vitro	Lower Premolar	2 walls	Yes	No	1: MOD + RCT + CR 2: same 1 +GFP 3: MOD + RCT + amalgam restoration 4: Same 3 +GFP	-Fracture resistance	There was no statistically significant difference between the two groups with GFP and the two groups without GFP
Scotti et al., 2015	Clinical retrospective	posterior teeth		Yes	No	1: fiber post's absence 2: fiber post's presence	longevity of ETT (3 years)	Direct restorations with fiber posts were statistically significantly better than restorations without posts.

Lin *et al.*, 2018	In vitro	Lower Premolar	2 walls	Yes	No	1: Restored with GFP with amalgam. 2: GFP with CR	-Fracture resistance -Fracture pattern	Fracture strength of fiber post and composite core restorations is significantly better than Nayyar's core amalgam restorations. Most fractures were favorable pattern.
da Rocha *et al.*, 2019	In vitro	Upper Premolar	2 walls	Yes	No	1: Glass ionomer cement + CR 2: metallic post + CR 3: GFP + CR 3:no RCT + CR	-Fracture resistance	No significant difference among the groups. Authors reported no mechanical advantage in using intraradicular posts in ETP with MOD cavity.
Mena-Álvarez *et al.*, 2020	In vitro	Upper Premolar	2 walls	Yes	No	1: FRC posts restored with resin 2: Elastic FRC posts restored with resin 3: FRC posts restored with FRC resin 4: Elastic FRC posts restored with FRC resin 5: MOD cavity with CR 6: MOD cavity with direct restoration with FRC resin	-Fracture resistance	No statistically significant difference between FRC post with CR and CR alone. The use of elastic FRC post increase the fracture resistance of ETP
Spicciarelli *et al.*, 2020	In vitro	Upper Premolar	2 walls 3 walls	Yes	No	1-G1 (3 residual walls) 2-G 2 (2 residual walls) 3 subgroups according to postendodontic restoration: no post (1), 1 post (2) or 2 posts (3)	Fracture resistance -Fracture pattern	Group with post significantly increased fracture than the group without a post. Group without post showed more unrestorable fractures.

1.2.6 Effect of horizontal glass fiber post (HGFP) on fracture resistance/pattern of ETT:

The concept of HGFP depends on its insertion through buccal and palatal cuspal walls of the tooth's cavity. Several *in vitro* studies have shown that placing HFGP increases the fracture resistance of ETT:

Beltrão *et al.* (2009) assessed the effect of an HGFP inserted through the buccal and palatal walls of an MOD cavity restored with CR on the fracture resistance of ETT. Seventy-five sound upper third molars were divided into five groups, of which one was a control group. The other groups underwent the following test after RCT: MOD+RCT, MOD+RCT+Post, MOD+RCT+CR, MOD+RCT+HGFP+CR. Findings showed significant improvement in the ETT's fracture resistance when HGFP was used in a MOD cavity restored with CR.

Srinivasan *et al.* (2013) evaluated the influence of several strengthening techniques with polyethylene and fiber post transfixed horizontally on the fracture strength of ETP with MOD cavities. Forty intact upper premolars receiving RCT and MOD cavity were distributed into four groups. Results showed that the fracture resistance was improved by HGFP and polythelene fiber placed within the CR restoration.

Karzoun *et al.* (2015) evaluated the influence of an HGFP on the fracture strength of upper ETP with MOD cavities. Sixty intact upper premolars were received RCT and divided into 5 test groups: Group1 control group (intact teeth), Group2 (MOD cavity without restoration), Group3 (MOD cavity with CR restoration), Group4 (MOD cavity with CR restoration and an HGFP), and Group 5 (MOD cavity with an HGFP only). It was concluded that the presence of an HGFP in a MOD cavity enhanced the ETP fracture resistance. However, HGFP group had more catastrophic fractures.

Favero *et al.* (2015) assessed the fracture strength of molars with MOD cavity directly restored with CR, with and without the presence of fiberglass posts. 84 extracted third molars divided into six groups: G1: sound teeth; G2: cavity preparation; G3:MOD + RCT; G4: resin composite; G5: MOD + RCT +2 HGFP 1.1 mm in diameter; G:6 MOD + RCT + 2 fiberglass posts 1.5 mm in diameter. Results showed that HGFP with CR significantly increased the fracture strength of ETT. The fracture site is unaffected.

Bromberg *et al.* (2016) assessed the fracture strength of restored direct and indirect MOD molar cavities. Fifty sound third molars were distributed into five groups: sound teeth, onlay, inlay, direct CR, and HGFP + direct CR. They concluded that transfixed fiberglass post plus direct CR significantly increases the fracture strength of ETT. However, the restored groups had the highest percentage of unrepairable fractures.

Aslan *et al.* (2018) compared the fracture resistance of ETP with MOD cavities with different coronal restoration techniques. One hundred five mandibular premolars were selected and distributed into seven groups: Group1: intact teeth (control), Group 2: unfilled MOD cavity, Group 3: MOD + CR, Group 4: 10-mm-long fiber post + CR, Group 5: 5-mm-long fiber post + CR, G6: Ribbond in the occlusal surface + CR, and Group 7: HGFP + CR. They concluded that using the HGFP or occlusal Ribbond improved the fracture resistance of ETP with MOD cavities. The favourable fracture type occurred more frequently than the unfavourable fracture type in all groups.

Bahari *et al.* (2019) compared the influence of different fiber strengthening techniques on the fracture strength of CR restored upper ETP. Seventy-two extracted premolars were divided into six groups: Intact teeth (positive control); ETT without restoration (negative control); CR restoration; placement of fibers at occlusal position; insertion of HGFP between buccal and palatal walls; After splinting the buccal and palatal walls with HGFP, fibers are placed at the occlusal position. No significant differences between all the experimental groups. The fracture pattern was more favourable in HGFP.

Mergulhão *et al.* (2019) assessed the fracture resistance and patterns of upper ETP with MOD cavities restored with different methods. Fifty extracted upper premolars. The teeth were divided into five groups. Group1: control group (intact teeth); Group2: conventional CR; Group3: conventional CR with an HGFP; Group4: bulk-fill flowable and bulk-fill CR; and Group5: ceramic inlay. Regarding fracture resistance no significant differences between groups. However, the presence of an HGFP decreased the unrepairable catastrophic fractures significantly.

Abou-Elnaga *et al.* (2019) evaluated the influence of traditional and truss access cavity preparations and artificial truss restoration (HGFP) on the fracture resistance of ETT. A total of sixty-six extracted lower first molars. The teeth were divided into four groups.

No significant difference between the groups for both fracture resistance and fracture pattern.

de Mesquita *et al.* (2021) compared the fracture resistance of ETP with MOD preparation using various restorative techniques. Sixty-four human premolars with one or two roots were divided into four groups. They found the restorative technique using a transfixed zirconia post increased fracture resistance and exhibited 100% recoverable fractures.

Ferri *et al.* (2021) evaluated the effect of fiber post placement on fracture strength and location in ETT. Forty healthy double-rooted first premolars were divided into five groups. 1: healthy teeth without intervention; 2: endodontic treatment with MOD cavity preparation; 3: restoration with CR; 4: fiber post placed horizontally in the center of the middle third of the crown; 5: fiber post placed horizontally 2 mm below the center of the middle third of the crown. They concluded that the use of fiber posts for restorations, regardless of their position, increases fracture resistance of ETT. Group with HGFP placement 2 mm below the center of the crown, most fractures occurred unfavourably. The horizontal placement of posts in the center of the crown is associated with a greater chance of fractures at the cusp level, which consider favourable fracture.

Bainy *et al.* (2021) investigated the influence of the use of HGFP on the fracture resistance of endodontically treated molars with class II mesio-occlusal cavity. Fifty upper third molars were divided into five groups: control group, no restoration; restoration with SonicFill 2® system; restoration with braided glass fiber and SonicFill 2® system; and restoration with HGFP and SonicFill 2® system. They found that the glass fiber, regardless of the composition, increased the fracture strength of ETT. Moreover, HGFP seems to influence favorable fractures more frequently than the other investigated groups.

More recently, Kim *et al.* (2020) documented the first clinical case using HGFP in an endodontically treated molar in an effort to enhance and strengthen the coronal structure.

The vast majority of the above studies (8 studies) indicate that ETT with HGFP showed significantly increased fracture resistance as compared to those restored without HGFP. However, a few studies (3 studies) showed that HGFP did not improve fracture resistance (comparable fractures resistance). Regarding fracture patterns of HGFP, three studies reported comparable fractures patterns, two studies reported more un-restorable fractures with HGFP, and Five reported that restorable fractures increased with HGFP.

Therefore, the current findings are still inconclusive to support the use of HGFP to reinforce ETT. In addition, none of the above studies investigated the effect of different types of root canal sealer with HGFP to increase ETT fracture resistance.

Configuration of MOD cavity might cause major biomechanical problems. Hood's hypothesis indicated that tooth cusps related to MOD cavity function as a cantilever beam. The extent of deflection under load is influenced by beam length and thickness (Hood, 1991) because the cavity floor acts as a fulcrum for cusp bending, and the cantilever length increases with the cavity depth. Based on this theory, the use of HGFP may be able to protect the cusps of teeth with MOD cavities if they are treated with this idea.

Tables 1.3 provides an overview of the methodology and outcomes of the studies referenced in this section.

Table 1.3: Summary of previous studies about the effect of HGFP on fracture resistance and fracture pattern of maxillary ETP with MOD cavities							
Author/Years	Control group	Test group	Total number and type of teeth	Type of post/coronal diameter	Type of composite resin	Evaluated outcomes	Results
Beltrao 2009 (Brazil) 1HGFP	G1: sound teeth. G2:MOD+RCT G3:MOD+RCT+CR	G1:MOD+RCT +HGFP G2:MOD+RCT +HGFP+CR	75 maxillary third molars	Glass fiber posts (Reforpost;Ângelus)	Filtek Z-250	FR: load on a universal testing machine with a crosshead speed of 1 mm/min on an inclined plane to the occlusal surface of the specimens parallel to the the surface-long axis of the teeth. Fracture pattern: analyzed under stereomicroscope X30; classified as Pulp chamber floor (non-restorable) and cusp fracture (restorable).	The HGFP in a MOD cavity significantly increased the FR of the teeth restored with resin composite compared to control group. HGFP group and control group showed comparable cusp fracture (restorable fracture).
Srinivasan 2013 (India)1HGFP	G1:MOD+RCT+CR G2:MOD+RCT+GFP G3:MOD+RCT+PEF+CR	G1:MOD+RCT +HGFP+CR	40 maxillary premolars	A fiber post (no. 11, Tenax fibre post, Coltène/Whaledent)	ParaCore, Coltène/ Whaledent	FR: load on a universal testing machine with a crosshead speed of 0.5mm/min on buccal and lingual cusps parallel to the long axis of the tooth.	There is significant difference between HGFP group and control group. In favor to HGFP $P < 0.01$
Karzoun et al 2015 (Syria)	G1: sound teeth G2:MOD no CR G3:MOD+RCT +CR	G:1 MOD+RCT+CR+HGFP G2:MOD+RCT +HGFP	60 upper premolars	Glass fiber posts (White Post DC no. 0.5; FGM Produtos Odontologicos Ltda, Joinville-SC, Brazil) of 1.4 mm diameter	Filtek Z250	FR: loaded with a crosshead speed of 1 mm parallel to the long axis of the tooth in a universal testing machine. Fracture pattern: analyzed visually; classified as cervical third fracture (restorable) middle and apical thirds (catastrophic	HGFP in a MOD cavity increased significantly the FR of the ETP compared to control group. Yet HGFP could not prevent catastrophic fracture.

Favero et al, 2015 (Brazil) 2HGFP	G1: Sound teeth G2: MOD G3: MOD +RCT G4: MOD +RCT + CR	G1: MOD+ RCT+ CR + 2 HGFP 1.1 mm in diameter. G2: MOD+ RCT + CR + 2 HGFP 1.5 mm in diameter	84 upper third molars	Glass fiber posts (Reforpost;Ângelus) 1.5 mm	Amelogen plus	FR: loaded with a crosshead speed of 1 mm parallel to the long axis of the tooth in a universal testing machine. Fracture pattern: analyzed under the magnifying lens; classified as Pulp chamber floor (non-restorable) and cusp fracture (restorable).	HGFP with CR significantly increased the FR of molars compared to the control group. The fracture pattern was similar between the tested groups.
Bromberg et al, 2016 (Brazil) 2HGFP	G1: sound teeth G2: MOD+ RCT+ only G3:MOD+ +RCT+ inlay G4: MOD+ RCT+ CR	G1: MOD+ RCT+ CR+ 2 HGFP	50 third molars	Glass fiber posts (Reforpost number 1,Angelus) 1.1mm	Filtek Z350 XT	FR: loaded with a crosshead speed of 1 mm on the occlusal surface parallel to the long axis of the tooth in a universal testing machine. Fracture pattern: analyzed under x3magnification; classified as not repairable (fracture of the pulp chamber floor) or repairable (fracture line involving the cusps fully or partially).	HGFP increased significantly the FR of molars compared to the control group. HGFP group had a high unrepairable fracture
Aslan et al 2018 (Turkey)	G1: intact teeth G2: unfilled MOD G3: MOD+RCT +CR G4: MOD+ 10 mm-long GFP+ CR G5: MOD+ RCT+5-mm-long GFP+ CR G6: MOD+ RCT+ Ribbond in the occlusal surface + CR	G1: MOD+RCT+HGFP+CR	105 mandibular premolars	Glass fiber post (RelyX™ Fiber Post)	Filtek Ultimate	FR: A universal testing machine loaded with a crosshead speed of 0.5 mm on the occlusal surface 45° oblique compressive. Fracture pattern: analyzed visual inspection as favorable (occurred in the cervical third of the root) or unfavorable (middle and apical thirds of the root)	HGFP group was significantly more resistant to fractures than the control ($P < 0.05$). HGFP exhibit more favorable fracture (significant)

Abou-Elnaga et al 2019 (Egypt)	G1: control group G2: MOD traditional access cavity+RCT. G3: MOD truss access cavity+RCT	G1: MOD artificial truss restoration+RCT (HGFP)	66 mandibular first molars	Glass fiber post (RelyX Blue; 3M ESPE, St Paul, MN) 1.9 mm	Polofil Nht, VOCO	FR: The samples were subjected to a vertical compressive force loaded at a crosshead speed of 1 mm/min parallels the tooth's long axis on the center of the occlusal surface of the samples. Fracture pattern: all the samples were visually inspected using a dental operating microscope (17X magnification) classified as either favorable fracture or unfavorable fracture. The favorable fracture was considered when the level of fracture dissipated to not more than 1 mm below the cervical margin of the sample.The unfavorable fracture was considered when the level of fracture dissipated to more than 1 mm below the cervical margin of the sample.	Non-significant difference between the groups for both FR and fracture pattern
Mergulha˜o et al. 2019 (Brazil)	G1: intact teeth G2:MOD+RCT+CR G4: MOD+ RCT+bulk-fill CR G5: RCT+ceramic inlay	G1:MOD+CR+ HGFP	50 maxillary premolars	Glass fiber posts (White Post DC number 0.5, FGM Produtos Odontolo´gicos) of 1.4 mm diameter	Filtek Z350. Filtek Bulk Fill Posterior	FR: compressive load on the long axis of the restored teeth at a crosshead speed of 1 mm/min on occlusal surface of the restoration on the buccal and lingual cusp inclines. Fracture pattern: by Stereomicroscope and classified as repairable when the fracture line was above the simulated bone level and unrepairable when the fracture line was below the simulated bone level (2mm below CEJ). SEM used for the studying of the fracture surface	Regarding FR no significant differences between groups. However, HGFP showed a significant difference for repairable fracture rates compared to control

Bahari et al 2019 (Iran)	G1: intact teeth G2: RCT+MOD G3: RCT+MOD+CR G4:RCT+MOD+PEF+CR	G1:RCT+MOD +HGFP+CR G2:RCT+MOD +PEF+HGFP +CR	72 Maxillary premolars	Glass fiber post (Angelus Ind. Prod. Odontológicos S/A, Londrina, PR, Brazil)	Valux Plus	FR: compressive force was applied at a crosshead speed of 0.5 mm/min parallel to the tooth long axis, in a universal testing machine. Fracture pattern: evaluated under a stereomicroscope at ×4 and categorized into favorable (fractures extending up to 1 mm below CEJ), unfavorable (fractures extending more than 1 mm below the CEJ).	No significant differences between all the experimental groups (p>0.05). The fracture pattern was more favourable in HGFP (significant)
Ferri et al 2021 (Brazil)	G1: Sound tooth G2: MOD+RCT G3: MOD+RCT+CR	G1:RCT+MOD + HGFP+CR (Post placed in the center of the middle third of the crown) G5:RCT+MOD + HGFP+CR (Post placed 2 mm below the center of the middle third of the crown)	40 maxillary first premolars	Glass fiber posts Reforpost (Angelus, Londrina, Brazil) 1.1mm.	Filtek Z250	FR: compressive stress was applied at a crosshead speed of 0.5 mm/min parallel to the long axis of the tooth in contact with the buccal and palatal cusp. Fracture pattern: by magnifying glass at 4X magnification, classified either as a pulp chamber floor fracture associated or not with the cusp, or as a cusp fracture only.	Using HGFP regardless of the position increases the fracture resistance of ETP compared to control. The presence of HGFP in the middle of the crown showed a more favourable fracture compared to control group.
Bainy et al 2021 (Brazil)	G1: Sound tooth G2: MO+RCT G3: MO+RCT+CR G4: MO+RCT+ braided glass fiber+ CR	G1: MO+RCT+ HGFP+ CR	50 maxillary third molars	Glass fiber posts Reforpost R (Angelus, Londrina, PR, Brazil) 1.1 mm	SonicFill 2	FR: compressive stress was applied at a crosshead speed of 0.5 mm/min parallel to the long axis of the tooth in contact with the buccal and palatal cusp using universal testing machine. Fracture pattern: by magnifying glass at 4X magnification, classified either as a pulp chamber floor fracture associated or not	HGFP, increases significantly the FR of molars compared to control. the use of HGFP provided 100% favorable fractures similar to sound tooth

						with the cusp, or as a cusp fracture only.	

MOD: Mesio-oculsal distal, RCT: Root canal treatment, CR: composite resin, HGFP: horizontal glass fiber post, PEF: polyethylene fiber, FR: fracture resistance, ETP: Endodontically treated premolars. SEM: scan electron microscope, MO: Mesio-oculsal. CEJ: cementoenamel junction.

Table 1.4 provides additional information on the methodology of the referenced studies as it is related to the inclusion of a thermocycling and dynamic loading protocol. It is interesting to note, that there are 6 studies that did not incorporate any thermal cycling or cyclic loading, 3 studies that included a thermocycling protocol, 1 study that used dynamic loading without thermocycling. There is only 1 study (Mergulhão *et al.*, 2019) that included both protocols in its methodology.

Table 1.4: additional summary of previous studies

Study	Thermocycling	Dynamic fatigue loading	Simulation of periodontal ligament (PDL)
Beltro et al. 2009	N	N	N
Srinivasan et al. 2013	thermocycling (6000 cycles at 5–55°C, dwell 30 s, transfer time 5 s)	N	N
Karzoun et al. 2015	N	N	Y
Favero et al. 2015	N	N	N
Bromberg et al. 2016	N	Cyclic fatigue loading with 500,000 cycles in distilled water at 37_C	N
Aslan et al. 2018	N	N	Y
Abou-Elnaga et al. 2019	N	N	N
Bahari et al. 2019	N	N	N
Mergulha˜o et al. 2019	Thermocycled between 5°C and 55°C in 5000 cycles	cyclic loading 50,000 times	Y
Bainy et al. 2021	Thermocycled between 5 ◦ C and 55◦ C for 500 cycles.	N	N
Ferri et al. 2021	Thermocycled at 5 ◦ C to 55 ◦ C for 500 cycles	N	N

Y: Yes, N: No

1.2.7 Root Canal Sealers

The primary goal of root canal sealers is to act as bonding agent between GP and canal wall, filling irregularities between the filling material and dentin walls, and entombing the remaining bacteria (Kapralos *et al.*, 2018). Sealers can also fill lateral and accessory canals where core obturation materials fail to reach.

There are many characteristics and requirements for an ideal root canal sealer. These include the ability to adhere to root dentin, be radiopaque, biocompatible, antibacterial, slow setting, dimensionally stable, and easily dissolved by solvents. Endodontic sealers are classified according to their composition: zinc oxide eugenol sealer, calcium hydroxide, epoxy resin-based sealer, glass ionomer, silicone-based sealer, MTA-based methacrylate-resin based sealer, and bio ceramic sealer.

Zinc oxide-eugenol-based sealers are among the early developed sealers that were relatively common worldwide. ZOE-based sealers rely on a chelation reaction between eugenol and the zinc ions for their setting (Tyagi *et al.*, 2013). ZOE-based sealers have shown long-lasting antimicrobial effects to various root canal bacteria, including *Enterococcus faecalis (E.faecalis),* and demonstrated minimal dimensional change, compared to other sealers (Orstavik, 1981; Upadhyay *et al.*, 2011). However, ZOE-based sealers have significant drawbacks, including high solubility, susceptibility to micro leakage, and cytotoxicity due to their formaldehyde release (el Sayed *et al.*, 1995; Tyagi *et al.*, 2013).

Epoxy resin-based sealers are among the most commonly used root canal sealers to date. Gutta Percha with the epoxy resin-based AH plus sealer is considered the gold standard in current obturation systems. These sealers are composed of a two paste system: an epoxide and an amine paste (Tyagi *et al.*, 2013). They have shown great stability and minimal dimensional change upon setting. They have also demonstrated good adhesion properties to root dentin due to their creep properties and long setting times that allow them to flow and penetrate the small crevices of the dentinal wall (Tyagi *et al.*, 2013; Cañadas *et al.*, 2014). Epoxy resin-based sealers have shown selective antibacterial effects, but mainly before their setting (Saleh *et al.*, 2004; AlShwaimi *et al.*, 2016). Although it is commonly known that pure epoxy resins can induce mutagenicity, little evidence is available on mutagenic effects exerted by the epoxide and amine-paste sealer system (Tyagi *et al.*, 2013). However, it has been reported that formaldehyde released from the sealer paste during setting can induce some local and systemic allergic reactions (Cohen *et al.*, 1998; Azar *et al.*, 2000).

Silicone-based sealers are composed of fine particles of GP embedded in a polymethylsiloxane silicone matrix. The silicone-based system combined the sealer and the core material as one entity injected into the canal space (Tyagi *et al.*, 2013). This sealer system demonstrated good flow properties, low solubility, low toxicity, and good adaptability (Tanomaru-Filho *et al.*, 2017). However, these sealers lack any antimicrobial properties and have shown poor wetting properties on root dentin (Shakya *et al.*, 2016).

Calcium hydroxide-based sealers: were introduced to the endodontic field in 1940 and later became popular for apexification, perforations sealing, resorption management, and as a root canal sealer (Leonardo *et al.*, 1980). The availability of free hydroxyl ions in this sealer results in a high pH that provides an antimicrobial activity (Bystrom *et al.*, 1985) and an alkaline phosphatase activator that plays an essential role in hard tissue formation (Stock, 1985). It diffuses through dentinal tubules and may connect with the PDL space to inhibit external root resorption and speed healing (Manhart, 1982). Calcium hydroxide–based sealers are not superior to other groups of sealers in their sealing or antibacterial activity and do not fulfill the criteria of the ideal sealer mentioned above due to its high solubility (Desai and Chandler, 2009).

Glass ionomer sealers: Glass ionomer cement endodontic sealer is a biocompatible sealer that chemically adheres to dental hard tissues (Jonck and Grobbelaar, 1992). It exhibits no shrinkage upon setting, possesses superior adaptation to the canal walls and is more radiopaque than Calcium hydroxide sealer (Ray and Seltzer, 1991), imparts resistance to vertical root fracture (Trope and Ray, 1992), and results in an acceptable clinical outcome (Friedman *et al.*, 1995). The main concern regarding glass ionomer sealer is irretrievability if retreatment is needed; while the sealer is retrievable using solvent and ultrasonic instrumentation (Friedman *et al.*, 1992), it is more time-consuming compared to ZOE and epoxy resin sealers (Moshonov *et al.*, 1994).

Methacrylate-resin-based sealers were introduced to the market as bondable sealers that bond the core filling material to the canal wall; to create a monoblock within the canal space. Methacrylate-based sealers were developed to establish micromechanical retention to root dentin (Kim *et al.*, 2010). Although the concept of producing a monoblock is highly desirable, it has many drawbacks. First, these sealers do not bond very well to conventional GP. A special coating of polybutadiene di-isocyanate methacrylate is recommended to cover the GP cone to allow for the adhesion between the resin sealer and the core material (Tyagi *et al.*, 2013). Second, due to the unfavourable cavity configuration of the root canal and lack of relief of shrinkage stresses during polymerization, pulling out of the resin tags from the dentinal tubules can occur, resulting in gaps at the sealer-dentin interface (Kim *et al.*, 2010).

MTA-based sealers: One of the most desirable features of MTA-based materials is their biocompatibility. Jiang *et al.* (2014) tested the cytotoxic effects of MTA-based sealers *in vitro* and reported insignificant cytotoxic effects on fibroblasts and human osteoblasts. When placed within the canal space, MTA releases calcium ions leading to an alkaline pH that stimulates regeneration of damaged tissues (Tyagi *et al.*, 2013). Due to the high alkalinity produced by MTA-based materials, previous studies have reported antibacterial effects against *E. faecalis* but mainly before setting of the material (Morgental *et al.*, 2011). Some of its limitations include; delayed setting time, negative colour alterations, difficult handling, and need for specific instruments (Tyagi *et al.*, 2013).

Hydraulic calcium silicate-based sealers (Bioceramic sealers) are composed mainly of tricalcium silicate, dicalcium silicates, calcium phosphate, colloidal silica, and calcium hydroxide (Al-Haddad and Che Ab Aziz, 2016). They also contain radio pacifiers and thickening agents to better deliver the material into the canal space (Al-Haddad and Che Ab Aziz, 2016). Bioceramic sealers have become very popular recently due to their favorable biological properties. They are biocompatible, chemically bond to root dentin, non-cytotoxic, dimensional stability, promote an alkaline pH, antimicrobial properties and release calcium and phosphate ions that induce hydroxyapatite formation (Al-Haddad and Che Ab Aziz, 2016; Poggio *et al.*, 2017). It also has a potential role to increase root strength after obturation (Wang, 2015). However, due to the chemical bond created during the hardening process, bioceramic sealers are harder to remove with conventional procedures in retreatment cases (Al-Haddad and Che Ab Aziz, 2016). These sealers are currently available in the market in two forms: powder/liquid or pre-mixed ready-to-use syringes.

One of the calcium silicate-based root canal sealers in the European market is **TotalFill® BC Sealer** (FKG Dentaire, La Chaux-de-Fonds, Switzerland). Additionally, this sealer is marketed under different brand names; EndoSequence BC Sealer (BUSA, Savannah, USA) and iRoot SP (Innovative BioCeramix, Vancouver, Canada) (Donnermeyer *et al.*, 2019). According to the supplier, this product consists of tricalcium silicate, dicalcium silicate, zirconium oxide, calcium hydroxide, monobasic calcium phosphate, tantalum oxide, and filler. TotalFill BC Sealer is a premixed calcium silicate-based compound that is ready to use. During setting, this root canal sealer absorbs humidity and sets within the root canal without mixing. It is biocompatible and cytocompatible. (Carvalho *et al.*, 2017; Gokturk *et al.*, 2017), chemically bond to dentin (Agrafioti *et al.*, 2015; Carvalho *et al.*, 2017).

Another new endodontic sealer containing calcium silicate is **Bioroot RCS** (Septodont, Saint-Maur-des-Fossés, France). It is composed of Powder: tricalcium silicate, zirconium oxide, and excipients; Liquid: aqueous solution of calcium chloride. After setting BioRoot, RCS releases calcium hydroxide (Camilleri, 2015), a calcium phosphate phase is formed when it contacts with a physiologic solution (Xuereb *et al.*, 2015). Due to the prolonged alkaline activity it exhibits numerous desirable properties; biocompatibility, chemical stability, hydroxyapatite formation, flowability, hydrophilicity, biomineralization, calcium ion release, and antibacterial properties.

1.2.7.1 Effect of Root canal sealers on fracture resistance of ETT

It has been demonstrated that endodontic sealer and endodontic obturation material should bond to the dentinal root canal to strengthen the remaining tooth structure and increase the fracture resistance of ETT. Thus, strengthening the tooth against root fracture and improving the long-term success of an ETT (Phukan *et al.*, 2017). However, studies have been inconsistent and conflicting evidence regarding the resistance of roots to fracture and the effect of endodontic sealers on them.

Chadha *et al.* (2010) evaluated the *in vitro* effect of different obturating materials on fracture resistance of mandibular premolar root canal treated teeth. They found that the fracture strength of the group obturated with Resilon-Epiphany was lower than that of the group obturated with AH Plus sealer and GP.

Ghoneim *et al.* (2011) evaluated and compared the fracture resistance of roots obturated using iRoot SP sealer and ActiV GP sealer systems. It was concluded that Bioceramic-based sealer (iRoot SP) increases resistance to fracture of endodontically treated roots.

Ulusoy *et al.* (2011) compared the influence of different endodontic sealers on fracture resistance of simulated immature teeth. It was concluded that iRootSP and Hybrid Root SEAL strengthen the simulated immature roots against fracture when used with GP or Resilon.

Sağsen *et al.* (2012) compared the fracture resistance of roots filled with GP and different endodontic sealers. They used an epoxy resin-based sealer (AH Plus) and two calcium silicate-based sealers (iRoot SP) and (MTA Fillapex). Among the three experimental groups, Fracture resistance was not found to be significantly different amongst the groups.

Javaheri *et al.* (2012) compared the fracture resistance of teeth restored with two obturation and two restorations. Forty single-canal premolars underwent MOD cavity. They were distributed into amalgam-Panavia F and composite and two obturation (GP-AH26 and Resilon-Epiphany). It was found no significant difference between Resilon-Epiphany and AH26.

Topçuoğlu *et al.* (2013) assessed the fracture strength of roots filled with three different root canal sealers. They used two bioceramic sealers (Endosequence BC sealer), MTA-based sealer, and epoxy resin-based sealer (AH Plus Jet). The results concluded that AH Plus Jet sealer and Endosequence BC increased resistance to fracture in root-filled premolar better than Tech Biosealer Endo.

Mandava *et al.* (2014) compared the effect of two resin sealers (AH Plus, MetaSEAL) and an MTA Fillapex sealer on the fracture resistance of ETT. The results showed that AH plus demonstrated the highest fracture resistance among the sealer groups

Celikten *et al.* (2015) compared the fracture resistance of roots filled with different endodontic obturation materials and sealers (ActiV GP obturation system, EndoSequence BC obturation system, and Smartpaste bio obturation system). They concluded that all the obturation materials used increased the fracture resistance of root canals. However, there were no significant differences between the three experimental groups.

Hegde and Arora (2015) Compared the fracture strength of roots canal obturated with three different hydrophilic materials, Resilon/Epiphany system, EndoSequence BC sealer, and GP/AHPlus system. The results showed that Hydrophilic obturations had been shown to reinforce the root canal's strength, thus increasing the fracture strength of the root.

Guneser *et al.* (2016) evaluated the VRF of roots obturated with a recently developed tricalcium silicate cement (BioRoot RCS) and compared it with iRoot SP sealer and MTA Fillapex sealer. They found no significant difference among them.

Patil *et al.* (2017) evaluated the VRF of lower incisor teeth, obturated using GP with three different sealers (epoxy resin-based sealer AH Plus®, calcium hydroxide-based sealer Apexit®, and EndoSequence® BioCeramic™). The result showed that the Bioceramic sealer group revealed better results.

Dibaji *et al.* (2017) assessed the fracture resistance of premolars roots after applying different sealers, including Epiphany, iRoot sealer, and AH-plus. No significant difference was found between the experimental groups.

Gervini *et al.* (2018) assessed the root fracture resistance of mandibular premolars using bioceramic Endosequence BC sealer and AH plus. The results showed statistically similar fracture resistance between the two obturation systems compared with untreated roots.

Uzunoglu Ozyurek and Aktemur Turker (2019) evaluated the influence of 3 different endodontic sealers (AH 26, MTA Plus, and BioRoot RCS) on the fracture resistance of roots-filled lower premolars. The results showed statistical similarities between AH 26 and BioRoot RCS, while statistically different from MTA Plus sealer.

Saba and ElAsfouri (2019) compared the effect of three different endodontic sealers (AH plus, Endoseal MTA sealer, and BioRoot RCS) on the fracture resistance of lower premolars. It was concluded that there was no statistically significant difference between all groups.

İnce Yusufoglu *et al.* (2019) assessed the fracture strength of roots shaping either with One Shape or ProTaper rotary systems and filled BioRoot RCS, AH Plus, and GuttaFlow. Results showed no significant differences between the groups.

Almohaimede *et al.* (2020) assessed the resistance of roots to fracture using two types of root canal sealers; TotalFill and AH Plus. Results found TotalFill group had slightly superior fracture resistance than the AH Plus group. However, no statistically significant difference was revealed between the two groups.

Mohammed and Al-Zaka (2020) compared the influence of different endodontic sealers on the fracture resistance of ETT using AH Plus, GuttaFlow 2, MTA-Fillapex, and TotalFillR BC™ sealers. It was concluded that TotalFill sealer was better when compared with other sealers.

It should be emphasized that, in all studies listed above, the teeth were decoronated [cutting the crown at the cementoenamel junction (CEJ)], except the study of Javaheri *et al.* (2012).

Recently, the influence of root canal sealers on ETT fracture resistance was evaluated by a systematic review (Uzunoglu-Özyürek *et al.*, 2018). They concluded that using an endodontic sealer increases the fracture resistance of ETT. However, the included studies had a high risk of bias. There were no conclusions that could be drawn about which sealer type was better than another.

Based on the above studies, it can be concluded that root canal sealers increase the fracture resistance of ETT with slightly favouring the bioceramic sealer. However, the difference is not statistically significant. In addition, all the above studies, except one, used decoronated teeth.

1.2.8 Finite element analysis method

Finite element analysis is a computer-based method utilized to simulate different complex engineering scenarios in order to subsequently solve related problems. Finite element analysis has been widely used to investigate mechanical behaviour in many fields like aeronautical and automotive. It is also used to assess biomechanical behaviour in the medical field, like osteoporotic fracture prognosis, tooth reconstruction, and temporomandibular replacement (Diarra *et al.*, 2016; Lee *et al.*, 2019). Indeed, FEA provides real simulation of stress distribution in teeth and restorations. It facilitates understanding the tooth biomechanics and represents a valuable biomimetic approach in restorative dentistry. The "von Mises stress criterion" - a measure used to assess various stress components, including tensile, compressive, and shear stresses, alone or in combination - is utilized to interpret the results in this framework. The entire stress field, which is widely used to indicate the possibility that damage will happen, represents the basis of Von Mises stresses (Pegoretti *et al.*, 2002). With the recent emerging and continuing evolution in bioimaging techniques, such as computed tomography (CT) and micro-computed tomography (μ CT), which are used to create high-quality 3D models of complex biostructures, the accuracy of FEA is made real.

In brief, FEA involves first developing solid models created using CT, micro-CT, or magnetic resonance image (MRI) datasets. 2D slices obtained from the datasets are then segmented using specialized software in order to develop a 3D rendering of the analyzed object. After that, a mesh is created from the rendered 3D solid model; the above-mentioned mesh is based on the idea of discretization of the solid into smaller geometric shapes that allow numerical model evaluation. The aforementioned mesh represents the basic working unit in FEA, and hence it is imported into FEA software for the intended analyses. First, the model is subjected to loads, boundary conditions, and mechanical material properties. Then stress distributions can be analyzed either qualitatively or quantitatively (Ko *et al.*, 2012).

The stresses in dowel-restored teeth were analyzed using the FEA method (Asmussen *et al.*, 2005). The investigators looked at material, shape, bonding, elasticity modulus, diameter, and length of the dowel. All dowel-related variables impacted the stress field generated in dowel-restored teeth.

Soares *et al.* (2008a) evaluated the influence of GFP and cavity design on ETP stress distributions and fracture resistance. The FEA revealed similar Von Mises equivalent stress distributions for the sound teeth. The findings also demonstrated that comparable materials (e.g., enamel, dentin, etc.) exhibited the same stress patterns in these groups without posts. The groups with a post had higher levels of stress in the composite and cuspal regions.

Soares *et al.* (2008b) analyzed the effect of restorative material and cavity design on stress distribution in upper premolars. FEA revealed that the models restored with direct CR and indirect ceramic restorations had similar stress distributions levels within tooth structure when compared to sound teeth. The stress distributions of the nonrestored numerical and restored numerical models with amalgam and laboratory-processed resin were similar, with significant stress concentration levels at the cavity preparation and root canal walls.

Soares *et al.* (2008d) assessed the effect of restorative treatment and RCT on the fracture resistance of MOD cavities premolars. The following dental structures revealed high-stress concentration in the non-restored models for stress distribution: internal angles and pulp chamber (MOD preparation model) and root canal walls (MOD preparation +RCT model). In contrast, the tooth restored with CR (MOD preparation plus CR restoration model) and (MOD preparation plus RCT plus CR restoration model) showed stress distribution comparable to the sound tooth model.

Lin *et al.* (2008) investigated the biomechanical interactions between restorative materials and cuspal preparation designs in a premolar with cusp-replacing by adhesive restoration using FEA. A cusp reduction of at least 1.5 mm was recommended to increase premolars' fracture resistance.

Al-Omiri *et al.* (2011) analyzed the stress concentration areas on upper ETP restored with a post-retained crown under several conditions using FEA. It was proposed that stress concentrations at the cervical level could be higher whether or not a post is present.

Kantardzić *et al.* (2012) evaluated how stress values in a 3D solid model of an upper premolar restored with CR were affected by cavity design preparation. MOD cavity designs were simulated using nine different cavity wall thicknesses and three different cusp reduction methods. Direct CR restoration was used to simulate all MOD cavities. Palatal cusp reduction was suggested to reduce stress in dental structures and restoration.

Navimipour *et al.* (2015) assessed the influence of three techniques of glass fiber insertion on stress distribution pattern of the upper ETP using the FEA method. Four models of upper ETP with MOD cavities. Circumferential fiber had minimal influence on total stress concentration, but it provided a better distribution of stress in the cervical region. However, the cuspal movement was not reduced by occlusal fiber.

Maravić *et al.* (2018) analyzed the influence of cusp reduction and/or an FRC post with CR on the von Mises stress distribution in dental structure using a 3D model of an upper ETP. Results concluded that the models with FRC posts had decreased stress distribution at high-stress locations and across the entire tooth model. Furthermore, they advised dentists reduction of palatal cusp could improve the tooth's durability and restoration.

Kantardžić *et al.* (2018) investigated the impact of cusp reduction, cavity isthmus width, and restorative material on stress distribution of premolar with MOD cavity. Upper premolar three-dimensional (3D) models were used using computed tomography (CT) for numerical simulations. Four restorative materials (direct CR, direct CR with GIC as the base, indirect CR, ceramic), and three cavity preparation designs. The study findings revealed that the cavity preparation design had the most influence on stress values in enamel, whereas restorative material had the greatest influence on dentin. It was recommended that the premolars with MOD cavities should be restored with a ceramic restoration that covered the tooth's palatal and buccal cusps.

da Rocha *et al.* (2019) evaluated the effect of the restorative technique on the fracture resistance of upper ETP with MOD cavity by using both fracture test and FEA. The results found that intraradicular posts have no mechanical advantage when an ETP requires MOD restoration.

Zarow *et al.* (2020) used FEA to assess the influence of fiber post placement on stress distribution in maxillary ETP with MOD. Four models of ETP with MOD cavities restored with: CR; composite and one fiber post in the palatal root; composite and one fiber post in the buccal root; or composite and two fiber posts. They concluded that the highest stress values recorded on dentin appeared slightly lower in the presence of fiber posts compared to ETT restored without post. Fiber posts in upper premolars with MOD cavities allows a positive distribution of occlusal forces, preventing dangerous stress concentration.

Borges *et al.* (2021) evaluated the stress distribution in MOD root-filled molars restored with both horizontal or vertical GFP and CR. Four models were analysed as follow: (Group1, control model), vertical GFP (Group2), HGFP (Group3), and vertical and HGFP (Group4). The findings revealed that stress patterns were comparable regardless of whether the glass fiber was present or not. HGFP created stresses that are similar to the absence of a post and are not recommended to improve the mechanical behavior of ETT.

All above studies (except one) used intra radicular posts (not HGFP), and there were conflicting results about using intraradicular posts to relieve the stress concentration.

1.2.9 Testing failure of endodontically treated teeth

1.2.9.1 Methods

A- Clinical

Many clinical studies have been conducted to evaluate long-term clinical outcomes of ETT restored with or without fiber post. In these studies, patients were subjected to clinical and radiographic evaluation to determine the survival and failure rates of ETTs (Mannocci *et al.*, 2002; Ferrari *et al.*, 2012). Causes of failure included post-decementation, post-fracture, root fracture, clinical and/or radiographic signs of a marginal gap between tooth and restoration, and clinical signs of secondary caries next to the restoration margins.

Another evaluation of clinical performance was based on the presence or absence of biological/technical failures. Endodontic failure, recurrent caries, or recurrent periodontitis were considered biological failures. Loss of retention or root fracture were considered technical failures (Guldener *et al.*, 2017).

B- In vitro

Laboratory mechanical fracture resistance testing based on static compressive load has been conducted to evaluate failure load, and failure mode of ETT restored with or without glass FRC posts. The method, also known as the crunch-the-crown test, exerts an axially compressive force to the specimen at a constant strain rate until a fracture occurs by a universal testing machine. Loads generated under these conditions are considerably higher than those found during normal function. The restorations are subjected to a wide spectrum of low-intensity stresses and degrade or fail as a result of accumulated damage from cyclic repetitive functional loading in a thermally changing, aqueous environment rather than a single-cycle loading event (Lima *et al.*, 2021). For this reason, tests of fracture load are not considered reliable predictors of clinical failure in CR restorations (Belli *et al.*, 2014). Fracture failures are frequently caused by cyclic loading damage rather than a single-cycle overloading event; consequently, the fatigue parameters of CR restorations may aid in predicting their clinical performance (Ferracane, 2013). Fatigue is a mechanical degradation process (Zhang *et al.*, 2015) in which repetitive or cyclic stresses reduce the load-bearing capacity of a material or restored teeth, resulting in the accumulation and propagation of damage or subcritical flaws at subcritical loads (Arola, 2017). To predict in vivo behavior of CR, *in vitro* setups should mimic the clinical environment to match the degradation processes as present in the oral cavity. These conditions can be simulated by thermomechanical loading that involves thermocycling (aging) to mimic thermal changes in the oral cavity and dynamic loading (fatigue) protocols to simulate oral chewing function (Morresi *et al.*, 2014; Blumer *et al.*, 2015). The aging method mimics what could happen over time when restoration and surrounding structures become more brittle. The propagated cracks may eventually merge and cause chipping or fractures (Lima *et al.*, 2021). The mechanical cyclic loading method can generate fluctuating stresses within the restoration and adjacent tooth structures. Fatigue degradation of the restored tooth structure may cause failure due to accumulation of minor damages, including crack generation and propagation and wear and surface irregularities which may lead to loss of anatomical shape, marginal breakdown, and eventual fracture (Lima *et al.*, 2021).

C- Others

Finite element method

Finite element analysis has been proven to be a useful tool for analyzing complex biological structures such as teeth. Exploring the stress distribution is important to understand the biomechanical behaviour of the tooth/restoration complex (Kantardzić *et al.*, 2012). *In vitro* fracture resistance tests only measure the endpoint in the failure process. Internal stress maps can be identified as valuable information about the sites which are more prone to failure initiation. FEA has been proposed as a valuable tool for complex structure analysis. Hence, appropriate FEA can be used to determine stress distribution and tensile stress of tooth/restoration complex.

Photo-elastic analysis

Photoelasticity is an experimental technique used to determine the stress distribution within a material. This method is based on an optomechanical property called birefringence, inherent in transparent optical materials (Fernandes *et al.*, 2003). The method of photoelastic stress analysis requires the use of two types of optical elements, a polarizer, and a waveplate. A polarizer consists of a polymer sheet with microscopic crystals embedded within the layers. The polarizer is fabricated such that all of these microscopic crystals are aligned to have the same molecular orientation. A waveplate consists of a birefringent crystalline material. Photoelastic analysis is easily conducted and proven to be a valid methodology to evaluate stress distribution (Glisson *et al.*, 2000). However, the properties of dental tissue are different from those of photoelastic materials. In addition, it is technically challenging to simulate objects composed of more than one substance (Fernandes and Dessai, 2001).

1.2.9.2. Assessing fracture patterns/failures

After conducting a fracture resistance test, there are different methods for evaluating ETT fracture pattern and failure mode, including visual inspection, stereomicroscope, fractographic analysis using a scan electron microscope, and micro-CT. These methods assess the location, type, and restorability of the fracture. This dissertation utilized visual inspection with a stereomicroscope to evaluate fracture of ETT because stereomicroscope is the most common method to determine the failure mode in the literature.

Chapter 2: Aims and objectives

2.1 Aim

The aim of this *in vitro* study was to test the reinforcement potential of a HGFP for maxillary ETP with MOD composite restorations and using different types of root canal sealers

2.2 Objectives

1. To test fracture resistance and evaluate fracture pattern of maxillary ETPs with restored MOD cavities with and without a HGFP *in vitro*.
2. To test the influence of different root canal sealers on maxillary ETPs' fracture resistance and fracture pattern with restored MOD cavities, with and without HGFP in vitro.
3. To analyze the stress distribution of a maxillary ETP with restored MOD cavity with and without HGFP using FEA.

2.3 Null Hypothesis

1. A HGFP post does not affect fracture resistance or fracture pattern in maxillary ETP with MOD cavities restored with direct CR.

2. Different root canal sealers do not affect fracture resistance or fracture pattern in maxillary ETP with MOD cavities restored with direct CR.

3. HGFP post does not affect the stress distribution in maxillary ETP with MOD cavities restored with CR.

Ethical considerations

The study proposal was submitted to the Biomedical Research Ethics Committee of the University of the Western Cape for ethics clearance (Ethics Reference Number BM 18/8/7).

Conflict of interest statement: No conflict of interest is declared.

Chapter 3: Materials and methods

This study was conducted as a collaboration between the University of Western Cape and the University of Missouri - Kansas City. The first part of the study (*in-vitro*) was conducted at the Oral and Dental Research Laboratory of the University of Western Cape. The second part (FEA) was developed and analyzed at the civil and mechanical engineering department of the University of Missouri - Kansas City.

3.1 Study design

This is an *in-vitro* comparative study.

3.2 Materials:

The restorative materials used in this study are listed in Table 3.1.

Table 3.1: Materials used in this study with their code, scientific name and supplied manufacturer

Material	**Manufacturer**	**Batch number**
AH plus sealer	Dentsply-DeTrey Konstanz, Germany	1901001069
TotalFill BC sealer and TotalFill BC Points	FKG Dentaire SA La Chaux-de-Fonds, Switzerland	18004SP 5440W
BioRoot™ RCS sealer	Septodont, Saint-Maur-des-Fosses, France	B22533
Resin composite	3M ESPE Filtek Z250 XT; Neuss, Germany	N986620 N988755
Resin composite (Flowable Restorative)	3M ESPE Filtek Z 350 XT	NA17609
Fiber Post	3M ESPE, RelyX	407741812
Self-adhesive resin cement	3M ESPE, RelyX U200 Automix	4853318
Dentin bonding agent	Single Bond Universal, 3M ESPE	90123C 4791226
Gutta-Percha Point	Dentsply	353922K

3.3 Methods

3.3.1 Methods of *in vitro* project

3.3.1.1 Sample size calculation:

The mean fracture load values for the control and HGFP groups were obtained from two previous studies: Karzoun *et al.* (2015) (994 N±147 and 961±245, respectively) and Mergulhão *et al.* (2019) (949 N±331and 934±233, respectively). We set alpha (α) level at 0.05 (5%), and beta (β) level at 0.2 (20%) (i.e. power=80%). With these parameters and using G*Power software version 3.1.9.2, the required sample sizes were 1180 and 11434, respectively. These were unrealistic sample sizes that would exhaust resources and require a high level of control. In addition, the evaluation of fracture patterns is of higher clinical relevance than fracture values. Accordingly, it was decided to take a sample size comparable to one of these two mentioned studies: 60 and 50, respectively. So, a sample of 60 teeth was deemed realistic. Nevertheless, we calculated the power of our study after completion using the same software mentioned above; the study power was 61% which is acceptable.

3.3.1.2 Sample selection:

Sixty freshly extracted upper premolars (single or two rooted), which were removed for periodontal or orthodontics reasons, were used and stored in 0.1% thymol solution. The teeth were free of caries, restorations, fractures, and damage from extractions. Teeth with curved roots or atypically shaped roots were excluded. All teeth were cleaned with a hand scaler. During preparation and testing, the teeth were kept at room temperature in distilled water. The means of buccolingual and mesiodistal dimensions were 9.1±0.5 mm, 6.5±0.5mm, respectively.

3.3.1.3 Root Canal Treatment Procedures:

Round burs (Komet Dental. Gebr. Brasseler GmbH. Germany) were used to prepare endodontic access cavities. To ensure canal patency, a K-file (#10) was moved down into the root canal until the file tip visible through the apex of the root. The file length was measured, and the working length was determined to be 1 mm less. ProTaper Next system (Dentsply Maillefer) used for root canal instrumentation procedures, it contains nickel-titanium (NiTi) alloy rotary instruments (M-Wire) and the X-Smart-Endo-motor (Dentsply Maillefer). The canals were prepared up to file X2 (0.25 mm tip and 6%

taper). Irrigation was performed by 2.5% NaOCl solution between instrument changes, 5 mL 17% EDTA for 1 minute as a final rinse, and sterile saline as a final flush. Paper points were used to dry the root canals. (Protaper, Dentsply Maillefer). Root canals were obturated using different sealers and the matched-tapered GP cones. The obturation specifics for each group are described in the next section. The access cavities were sealed with a temporary restorative material (Coltosol, Coltene, Brazil). The sealers were mixed according to the manufacturer's specifications.

3.3.1.4 Specimens grouping:

Teeth were randomly divided into six equal groups (n=10) according to the root canal sealer and HGFP used:

Group 1: GP + AH Plus sealer

Group 2: TotalFill BC Points (Coated GP) + TotalFill BC sealer

Group 3: GP + BioRoot RCS sealer

Group 4: same group 1 + HGFP

Group 5: same group 2 + HGFP

Group 6: same group 3 + HGFP

For Groups 1 and 4, the AH Plus sealer was introduced into the canal using a paper point, then the protaper next GP point size 25 corresponding to the final instrument size was introduced into the canal up to working length.

For Groups 2 and 5, the premixed TotalFill BC sealer was injected into the root canal using the intracanal tip supplied by the manufacturer. The apical part was filled and the tip slowly withdrawn while injecting the sealer completely filling the canal. The TotalFill BC points size 25 were then be introduced into the canal up to working length.

For Groups 3 and 6, the powder and liquid of BioRoot RCS sealer is mixed according to manufacture; then, the root canal walls were covered with sealer using paper points; then, Coating the GP point with sealer and inserting it into the root canal.

Excess GP was seared off with a hot plugger and the access cavity cleaned from excess sealers. The access cavities were sealed with temporary restorative material (Coltosol, Coltene, Brazil). The teeth were kept at room temperature in distilled water for at least 72 hours to ensure the complete set of the sealers.

Lines were drawn on the teeth to determine bone level simulation and CEJ (Figure 3.1). After that, the roots were centrally embedded in self-curing acrylic resin (self-cure acrylic resin, Shanghai, China) inside plastic tubing up to 2 mm below the CEJ to simulate the alveolar bone level without a simulated PDL. A parallelometer was used to ensure that the long axes of the teeth were perpendicular to the horizontal.

3.3.1.5 Specimens preparations:

Lines were drawn to determine the margins of MOD tooth preparation (Figure3.2). MOD cavity preparation was performed on all teeth. For all preparations, round-ended fissure bur #3131 (Komet Dental. Gebr. Brasseler GmbH. Germany) was used in a high-speed air-water spray handpiece mounted on a dental surveyor to standardize the preparation of all specimens (Figure 3.3). To obtain high cutting efficiency, fissure burs were replaced after six preparations.

The buccopalatal width of the occlusal isthmus was one-third of the intercuspal width. The buccopalatal width of the proximal box was one-third of the buccopalatal width of the crown (Figure 3.4). The gingival floor was located 1 mm above the CEJ. After finishing the preparation, all internal edges were rounded and smoothed (Figure 3.5). Only one operator performed all the cavity preparations. Periodontal probe was used to verify the preparations' dimensions.

The perforations for the horizontal post in the teeth of groups 4, 5, and 6 were made at the most prominent point on the buccal and palatal walls at the midpoint between mesial and distal. With air-water spray, the holes were made with round diamond burs #1013 (Komet Dental. Gebr. Brasseler GmbH. Germany). Each bur was replaced after six holes were drilled to obtain high cutting efficacy.

Figure 3.1: Lines are drawn; the first line from below represents bone level simulation (2mm below CEJ), the middle line represents CEJ, and the third line represents the margin of MOD cavity preparation (1 mm above the CEJ)

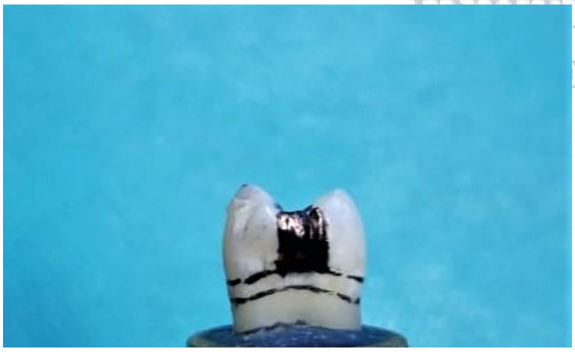

Figure 3.2: Lines are drawn to determine MOD tooth preparation

Figure 3.3: Dental surveyor adapted to hold high-speed handpiece parallel to the long axis of the tooth

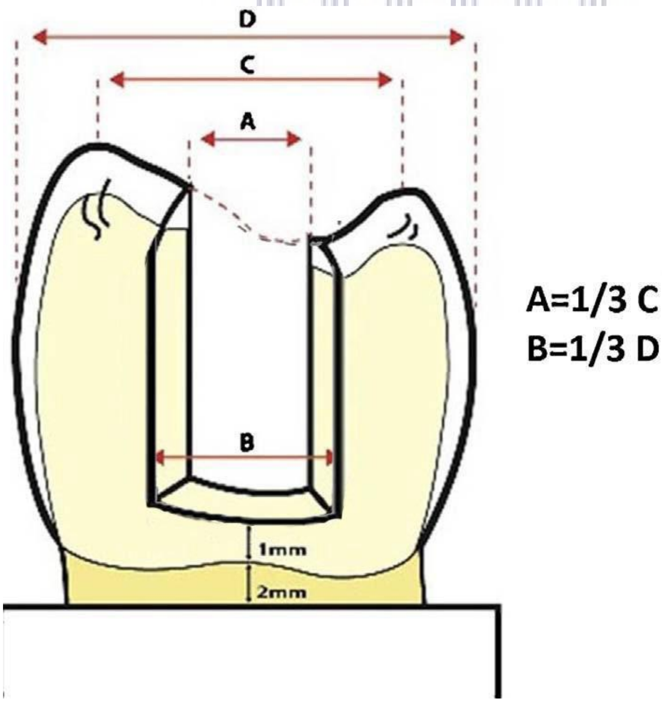

Figure 3.4: schematic diagram of the MOD cavity preparation: (A) Occlusal isthmus width, (B) Gingival floor width, (C) Intercuspal width, and (D) Buccopalatal width

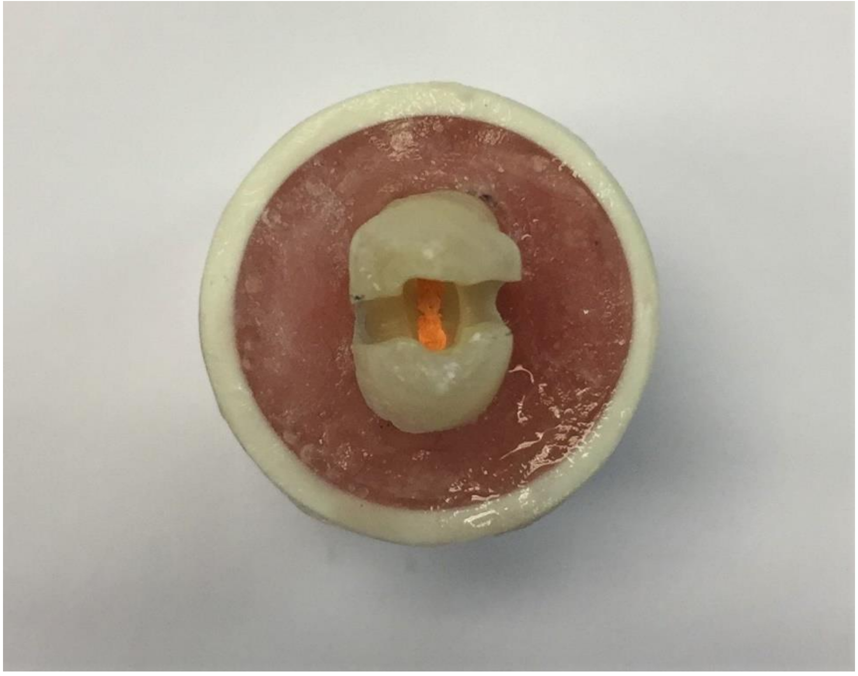

Figure 3.5: tooth after MOD preparation

3.3.1.6 Restorative Procedures:

The walls of the MOD cavities were etched for 15 seconds with 37% phosphoric acid (Meta Etchant; Meta Biomed Co.,Ltd., Cheongju-si, Chungbuk, Korea), rinsed with water spray, and allowed to air dry. After that, a dentin bonding agent (Single Bond Universal, 3M ESPE) was used to bond the MOD cavities. The flowable composite (3M ESPE Filtek Z 350 XT) was first applied to the root canal orifices and then polymerized from the proximal and occlusal areas. In groups 4, 5, and 6, glass fiber posts of 1.4 mm diameter (3M ESPE, RelyX) were cleaned with 70% alcohol and then fixed horizontally in the holes using self-adhesive resin cement according to the manufacturer's instructions (Figures 3.6 and 3.7). The extremities of the post were cut close to the buccal and palatal surfaces. A Tofflemire retainer was used to place a metal matrix band around the teeth. Then CR (FiltekZ250 XT; 3M/ESPE) was applied using the incremental layering technique. Each layer was 2 mm thick and cured with light for 20 seconds. After removing the matrix band and retainer, the boxes were post-cured for 40 seconds on each side on the buccal and lingual aspects. After that, all restored teeth were finished and polished using high-speed composite finishing burs (Mani, Japan) (Figure 3.8). Teeth were stored in distilled water in an incubator at 37°C and 100% humidity for 1 week before thermocycling.

Figure 3.6: Occlusal view of HGFP

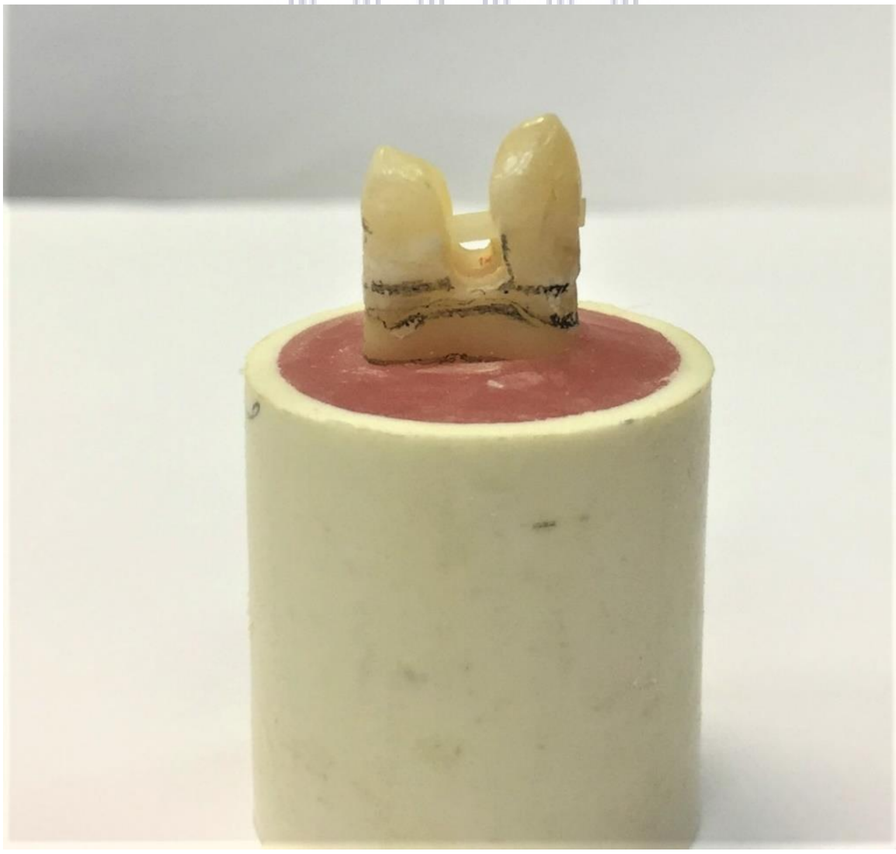

Figure 3.7: Lateral view of HGFP

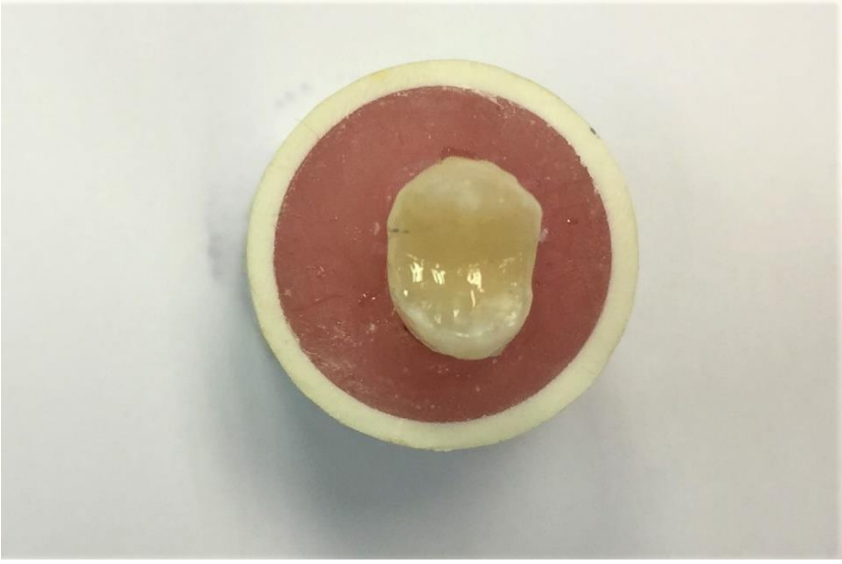

Figure 3.8: Tooth after restoration

3.3.1.7 Thermocycling and cyclic loading

All specimens underwent thermocycling for 5000 cycles between 5°C and 55°C in water with a 30-second dwell time at each temperature (SD Mechatronic thermocycler, Germany). This regimen represents six months of clinical function (Gale and Darvell, 1999; Amaral *et al.*, 2007). After thermocycling, the specimens were submitted to cyclic loading 50,000 times, representing approximately three to 12 months of clinical service (Wiskott *et al*., 1995) in a mechanical chewing simulator (CS-4.2 economy line, SD Mechatronik, GmbH, Feldkirchen-Westerham, Germany). The load is produced by weights mounted on a vertical bar. Although the chewing simulator contains two test chambers, only one test chamber was used because a force sensor (Force Measurement System KM-3, SD Mechatronik) was mounted on one of the two antagonists' holders. The mounting of a force sensor meant that testing had to be done in a dry environment. A loading cycle frequency of 2 Hz per second with a gradual load ranging from 0 to 50 N was selected to simulate physiologic masticatory forces. The specimens were mounted in the specimen holder in such a way that the standard 6mm diameter steel antagonist made even contact on the slopes of the buccal and palatal cusps, avoiding contact with the restoration. The contacts were tested with occlusal indicator paper (Figure 3.9) until 2 even occlusal contacts were achieved. The purpose of the force sensor was to monitor a consistent load at the tooth-antagonist interface during fatigue loading. The 3D force sensor measured the forces in three directions (X, Y, and Z) of the space during simulation.

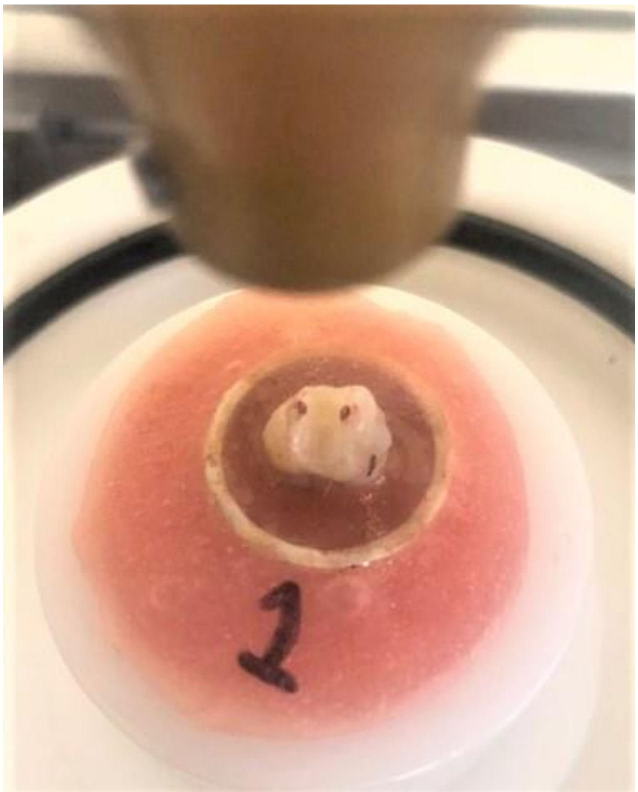

Figure 3.9: Occlusal contact points between the tooth sample and the antagonist

After completion of the cyclic loading, the specimens were mounted in the universal testing machine as described in the next section.

3.3.1.8 Fracture load

A 6 mm diameter stainless-steel cylinder bar fixed in a universal testing machine was used to determine fracture resistance. A universal tester (Tinius Olsen, UK) was used to apply a vertical compressive load on the same buccal and palatal contact points as established during chewing simulation (Figure 3.10). The crosshead speed was 1 mm/min. The machine settings were as follows: stress range 1500MPa, displacement range 2%, until load 1500, and height 2mm.

The compressive load needed to fracture was measured in Newtons (N). Force vs. distance curves were plotted for each tooth. The failure load was identified as the highest load prior to failure as found on the force versus distance graph (Figures 3.11 and 3.12).

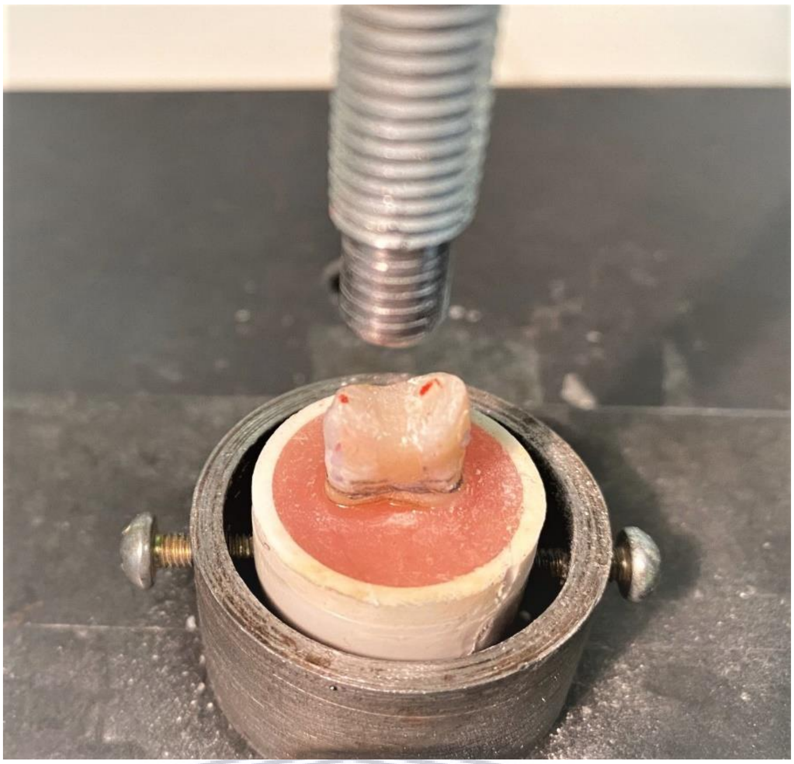

Figure 3.10: Occlusal contact point on the tooth before compressive load test

Figure 3.11: Typical load displacement curve (restored tooth without HGFP)

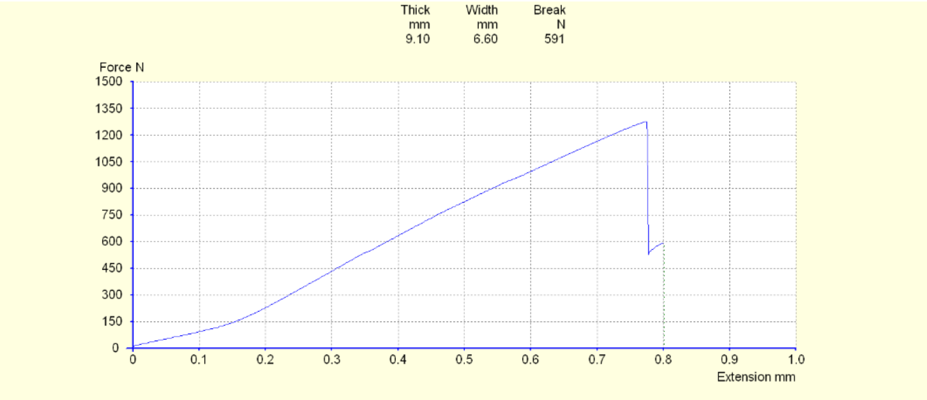

Figure3.12: Typical load displacement curve (restored tooth with HGFP)

3.3.1.9 Fracture patterns evaluation

The specimens were examined regarding the type, location, and failure mode. Fracture patterns were classified as restorable when the fracture line was above the simulated bone level and unrestorable when the fracture line was below the simulated bone level.

Subclassification of failure mode (cohesive, adhesive, mixed) (Sorrentino *et al.*, 2007; Taha *et al.*, 2011) was evaluated with the assessment criteria summarized in (Table 3.2)

Table 3.2: Classification of failure mode

Type	Failure mode	Description
I	Tooth cohesive	A fracture involving a coronal tooth portion, either enamel and/or dentin.
II	Adhesive	Fracture at the interface between the tooth and restoration and/or fiber post (debonding of restoration) either buccal or palatal wall
III	Restoration cohesive	Fracture within the restoration itself
IV	Mixed Cohesive/adhesive	Fracture is both adhesive and cohesive
V	Horizontal glass fiber post	Fracture of horizontal glass fiber post

The fracture patterns and failure mode assessments were visually and microscopically performed by two-examiners agreement using a stereomicroscope (Stemi 508, Zeiss, Oberkochen, Germany) at 20X magnification. Digital images of fracture patterns were captured using a digital camera (ZEISS Axiocam ERc 5s) fixed on the same stereomicroscope.

Reliability of assessment of fracture pattern and failure mode for all specimens (inter- and intra-observer) were done by kappa statistics.

Statistical analysis

Statistical analysis was performed using the IBM SPSS Statistics (SPSS for Windows, version 25; IBM Corp). The Kolmogrov–Smirnov test was used to test for the normal distribution of fracture resistance data. And the data were normally distributed (P = 0.080). The Levene test was used to test the homogeneity of variance. Descriptive data were presented as appropriate as percentages, frequencies, mean, and standard deviation. Then a Two-way ANOVA was used to test the interaction effect of HGFP and root canal sealer types on fracture resistance. Fracture patterns results were compared using Chi-square and Fisher exact test. The significance level was set at $\alpha < 0.05$.

3.3.2 Methodology of FEA part

Based on Micro-CT imaging, the second objective of the study was to develop two 3D FEA models of a restored extracted maxillary premolar without HGFP and the same tooth with HGFP and subject to loading.

A restored premolar was scanned at the CT Scanner Facility, Central Analytical Facilities (University of Stellenbosch), using micro-computed tomography (Micro-CT, General Electric Phoenix V|Tome|X L240 system, Wunstorff, Germany), settings at 220 kV and 200 µA with a voxel size set to 80 µm. The obtained data were converted to DICOM format, of pixels size 0.4235 and 512 resolutions. These files were imported into medical image processing software (MIMICS® 19, Materialise, Leuven, Belgium, www.materialise.com). The various hard tissues visible on the scans were identified by a segmentation process in MIMCS® based on image density thresholding using histograms of the density values in Hounsfield Units (HU). Typically, the dentin area falls within a range of 5,150 to 10,000 HU and the enamel from 10,001 to 12,297 (max) HU. With the help of MIMICS, a lower bound of 5,150 HU was chosen to remove as much noise as feasible while keeping as much of the original signal as possible. A series of advanced digital image processing techniques, such as region-growing, gap filling, and pixel closing, were then used to produce a virtually flawless set of images of the tooth. A solid model was created in MIMICS as a STL file from this set of images. The final solid surface model was created in Mimics and imported to 3-Matic® (www.materialise.com) as a STL file for meshing and FEA purposes.

The solid model had two parts namely, the tooth and the composite regions. For this study, the tooth (enamel and dentin) was considered as one unit.

The STL solid model, which is a triangulated surface representation of the solid model, was smoothed and created into a volume mesh using a non-manifold assembly process. The volume mesh of the model with no HGFP was created in 3-Matic and exported to FEBio as a ABAQUS input file format which is compatible with the FEBio program.

In order to create the finite element model of the tooth/composite with the horizontal fiber post, a separate model of the HGFP was created in FEBio (www.febio.org) as an STL file and imported into 3-Matic and positioned accurately relative to the tooth/composite by moving it into place. The HGFP was then added to the tooth/composite part using a create non-manifold process. This step allowed for creating a solid model with the tooth and HGFP. All parameters (enamel and dentin, dimensions of the HGFP, restorative materials) were simulated in a scenario similar to those used in the laboratory test.

The multi-region tooth segment finite element model was created in 3-Matic utilizing 4 -noded tetrahedral elements. The thresholding, model generation, smoothing, and mesh generation processes were repeated iteratively between the two softwares until a successful mesh was obtained.

After creating the 3D finite element volume mesh, the model was saved as a (. INP) file prior to importing into FEBio software suite (www.febio.org) for FE analysis. The mechanical properties of teeth, such as elastic modulus, density, and Poisson's ratio of teeth, are utilized to define the material used to simulate the tooth structure. The tooth model's regions were defined by their elastic mechanical properties. The elastic modulus varies between layers, whereas the Poisson's ratio and tooth density are considered to be constant. The elastic modulus values were taken from a previous study (Fei *et al.*, 2018). All FEA materials were considered linearly elastic and isotropic (Table 3.3), except for the HGFP, which was modelled as transversally orthotropic material (Table 3.4). Boundary and loading conditions were identical to the *in vitro* laboratory set up in order to allow comparison and validation of the model. Tetrahedral elements were used to mesh the geometric models. The total number of the first model included 83,142 node and 392,019 elements, and the second model included 886,542 node and 3,984,953 elements. Static vertical loads of 200 N and 800 N were applied through a 6mm diameter round bar on the node at the buccal and lingual cusps. The loads were applied as point loads over several nodes (numbers) along the points of contact of the bar with the buccal and lingual cusps (nodal loads). The stress distribution was recorded as colorimetric maps. The stress distribution patterns and the maximum von Mises stresses were described for the different structures (tooth, restorative materials, HFP, along the root and crown of the ETT).

Table 3.3: Mechanical properties of isotropic materials

Materials	Elastic modulus (MPa)	Poisson's ratio
Enamel	84 100	0.20
Dentin	18 600	0.31
Gutta-percha	69	0.45
Composite resin	12000	0.30

Table 3.4: Mechanical properties of orthotropic glass fiber post

Modulus of Elasticity (MPa)			Shear Modulus (MPa)			Poisson's Ratio		
Ex	Ey	Ez	Gxy	Gxz	Gyz	Vxy	Vxz	Vyz
37 000	9500	9500	3100	3500	3100	0.27	0.34	0.27

Chapter 4: Results

4.1 Results of *in vitro* project

4.1.1 Kappa statistics

Concerning the agreement (inter-examiner agreement) of readings among the examiners. Kappa values ranges from 0 (no agreement at all) to 1 (ideal agreement), with values over 0. 6 are considered good to excellent agreement

Inter-examiner agreement (first assessment) in failure mode ranged from a minimum of 0.643 (group 3) to a maximum 1 (groups 2, 5, and 6). The overall agreement in this variable was 0.88, which represents almost perfect agreement. Inter-examiner agreement in fracture patterns ranged from a minimum of 0.75 (group 1) to a maximum of 1 (groups 3, 4, 5, and 6). The overall agreement in this variable was 0.922, which represents almost perfect agreement.

Inter-examiner agreement (second assessment) in failure mode ranged from a minimum 0.667 (group 2) to a maximum 1 (groups 1, 3, and 5). The overall agreement in this variable was 0.88, which represents almost perfect agreement. Inter-examiner agreement in fracture patterns ranged from a minimum of 0.609 (group 5) to a maximum of 1 (groups 1, 2, and 3). The overall agreement in this variable was 0.887, which represents almost perfect agreement.

Intra-examiner agreement (first observer) in failure mode ranged from a minimum 0.805 (group 1) to maximum 1(groups 2, 3, 4, and 5). The overall agreement in this variable was 0.94, which represents almost perfect agreement. Intra-examiner agreement in fracture patterns ranged from a minimum of 0.78 (group 4) to a maximum of 1 (groups 1, 2, 3, 5, and 6). The overall agreement in this variable was 0.96, which represents almost perfect agreement.

Intra- examiner agreement (second observer) in failure mode ranged from minimum 0.64 (group 3) to a maximum of 1 (groups 1, 4, 5, and 6). The overall agreement in this variable was 0.88, which represents almost perfect agreement. Intra-examiner agreement in fracture patterns ranged from minimum 0.609 (group 5) to a maximum of 1 (groups 3 and 4). The overall agreement in this variable was 0.84, which represents almost perfect agreement.

4.1.2 Cyclic loading

In total, 95% of the specimens survived cyclic loading. Three specimens failed during dynamic fatigue loading, one from G1, one from G2, and one from G5. The three failed specimens' failure mode was adhesive failure, and the fracture patterns were unrestorable.

4.1.3 Fracture pattern

Two specimens were destroyed due to operator error while doing the static testing, one from G 1 and one from group 6.

Restorable fracture extended from the occlusal surface and ended above the simulated bone level, while the non-restorable fractures started from occlusal surface and ended under the simulated bone level. (Figures 4.1., 4.2, and 4.3)

Fracture patterns are presented in (Table 4.1). Overall, restorable fractures (above the simulated bone level) (Figure 4.4) occurred in 62% of all specimens, ranging from as low as 37% in G1 to as high as 89% in G5. Non-restorable fractures (catastrophic) (Figure 4.5) occurred in 38 % of all specimens, ranging from as low as 11% in G5 to as high as 63% in G1 (Table 4.1).

More restorable fractures were observed in groups with a HGFP (G4, G5, and G6) (Figure 4.6), representing 65 % of all restorable fractures as compared to the groups without HGFP (G1, G2, and G3) (Figure 4.7), representing 71% of non-restorable fractures.

Fisher exact test revealed a significant difference in fracture pattern between groups without HGFP and groups with HGFP; The group with a HGFP post had significantly more restorable fracture modes than the groups without HGFP post (P= 0.013) (Table 4.2).

Chi-Square test revealed insignificant difference of fracture pattern based on the different types of root canal sealers (P = 0.721) (Table 4.3).

Table 4.1: Fracture patterns of each group

Group	Fracture pattern		Total
	Restorable	Unrestorable	
Group 1	3 (37.5%)	5 (62.5%)	8
Group 2	4 (44.4%)	5 (55.6%)	9
Group 3	5 (50%)	5 (50%)	10
Group 4	7 (70%)	3 (30%)	10
Group 5	8 (88.9%)	1 (11.1%)	9
Group 6	7 (77.8%)	2 (22.2%)	9
Total	34 (61.8%)	21 (38.2%)	55

Table 4.2: Fisher exact test of fracture pattern based on HGFP

Groups	Fracture patterns		Total	P-Value
	Restorable	Non-Restorable		
Without HGFP	12 (44.4%)	15 (55.6%)	27	P 0.013*
With HGFP	22 (78.6%)	6 (21.4%)	28	
Total	34 (61%)	21 (38.2%)	55	

Table 4.3: Chi-Square test of fracture pattern based on the type of root canal sealer

Sealer type		Fracture pattern		P-value
	N	Restorable	Non-restorable	
AH sealer	18	10 (55.6%)	8 (44.4%)	0.721
TotalFill sealer	18	11 (61.1%)	7 (38.9%)	
BioRoot sealer	19	13 (68.4%)	6 (31.6%)	

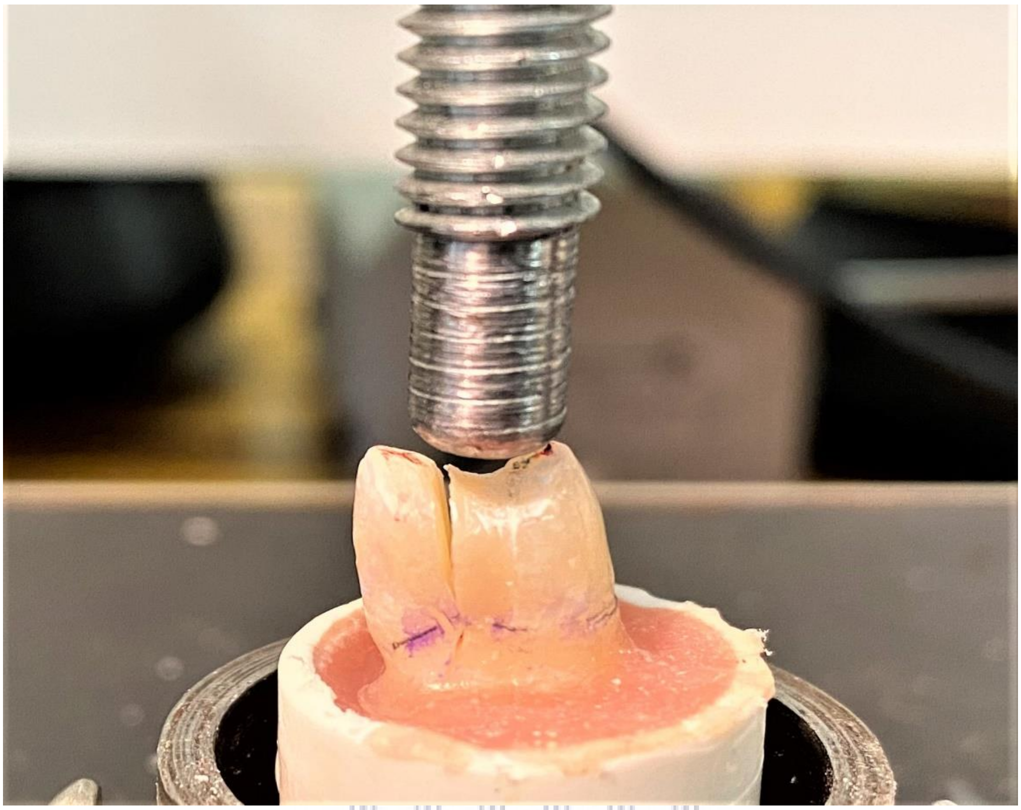

Figure 4.1: Lateral view after tooth fracture.

Figure 4.2: Occlusal view after tooth fracture.

Figure 4.3: Occlusal view after tooth fracture, showing the HGFP.

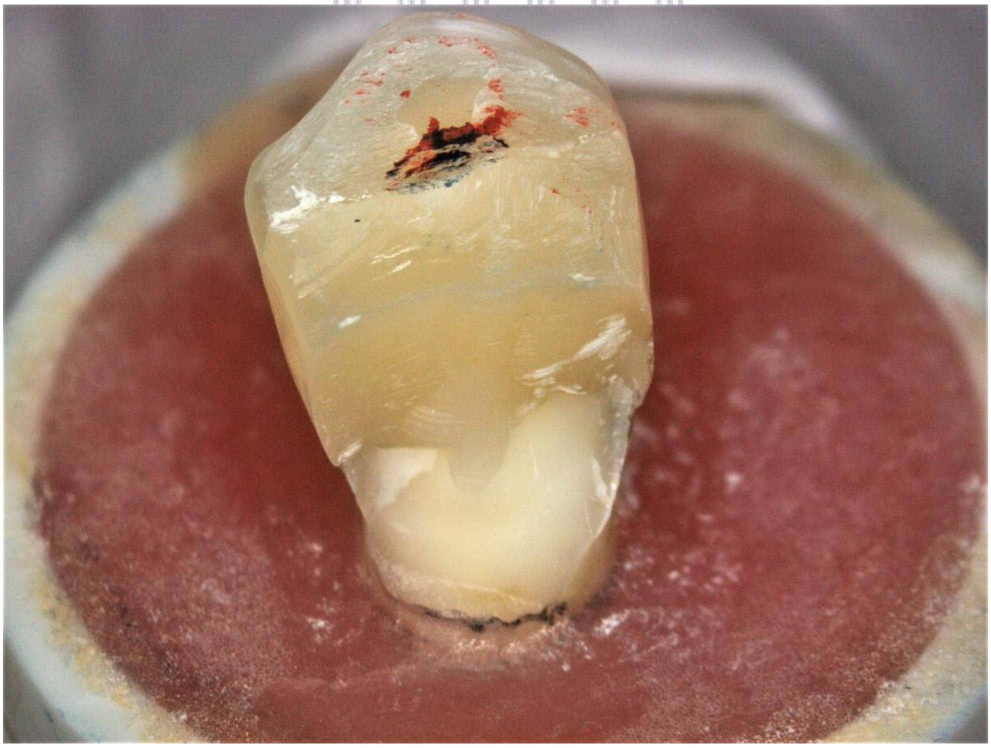

Figure 4.4: Example of restorable fracture of ETP without HGFP.

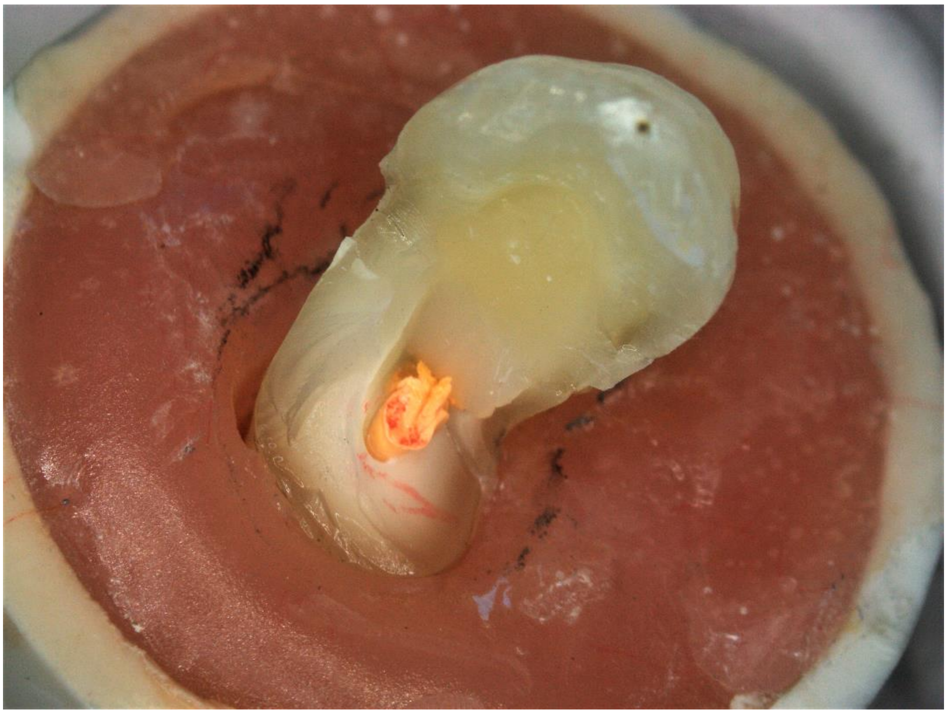

Figure 4.5: Example of a non-restorable fracture without HGFP.

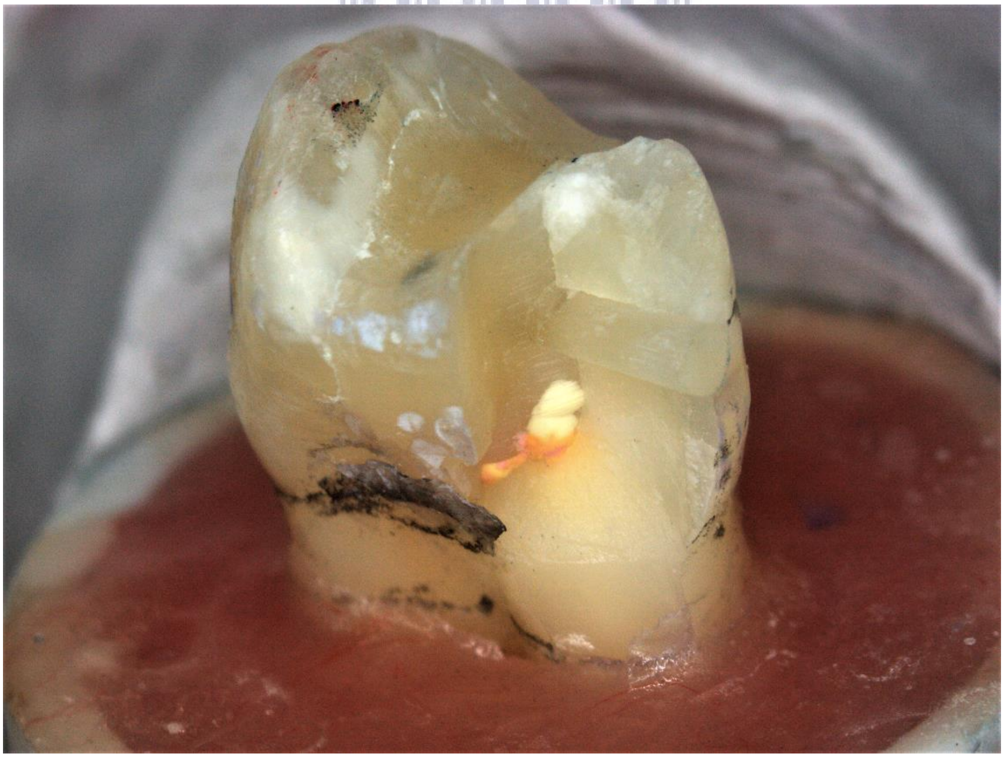

Figure 4.6: Example of restorable fracture with HGFP.

Figure 4.7: Example of non-restorable fracture with HGFP.

4.1.4 Failure mode

The mode of failure is presented in (Table 4.4). The majority of specimens displayed tooth cohesive (40%) or mixed failure (35%). Twenty-five % were adhesive failures.

For type I (tooth cohesive failure), cohesive failures within tooth crown without debonding were common. G 4 and 5 recorded the highest (50%), (56%) respectively followed G 2 (44%), whereas G 3 recorded the lowest (20%) (Figures 4.8 and 4.9).

For type II (adhesive failure), G 3 recorded the highest (50%), followed by G 1 (30%), whereas G 4 and 5 showed the least (10%). Debonding of the restoration started from occlusal surface at the palatal interface (palatal-occlusal line angle) with the cavity wall. The crack initiated at palatal-occlusal line angle, and then all cracks propagated obliquely to the palatal root surface, causing a deflection of the tooth wall and, as a result, palatal wall fracture (Figures 4.10 and 4.11).

For type III (mixed failure), mixed failure occurred predominately in the tooth cusp and the outer part of the restoration. G 4 and 6 recorded the highest (44%), (40%) respectively, followed by G 5 (33%) and G 3 (30%), whereas G 1 recorded the lowest (25) % (Figures 4.12 and 4.13). One specimen recorded cleavage of both buccal and palatal walls through the middle level of the tooth.

Notably, most of the cohesive fracture occurred in groups with HGFP, while adhesive fracture occurred in groups without HGFP.

There were no fractures of the HGFP observed or restoration cohesive failure.

Table 4.4: Failure mode of each group

Groups	N	Type I Tooth cohesive	Type II Adhesive	Type III Mixed	Type IV Restoration cohesive	Type V HGFP
G1 AH sealer	8	3 (37.5%)	3 (37.5%)	2 (25%)	0	-
G2 TotalFill sealer	9	4 (44.4%)	2 (22%)	3 (33%)	0	-
G3 BioRoot sealer	10	2 (20%)	5 (50%)	3 (30%)	0	-
G4 AH sealer with HGFP	10	5 (50%)	1 (10%)	4 (40%)	0	0
G5 TotalFill sealer with HGFP	9	5 (56%)	1 (11%)	3 (33%)	0	0
G6 BioRoot sealer with HGFP	9	3 (33%)	2 (22%)	4 (44%)	0	0
Total	55	22 40%	14 25%	19 35%	0 0%	0 0%

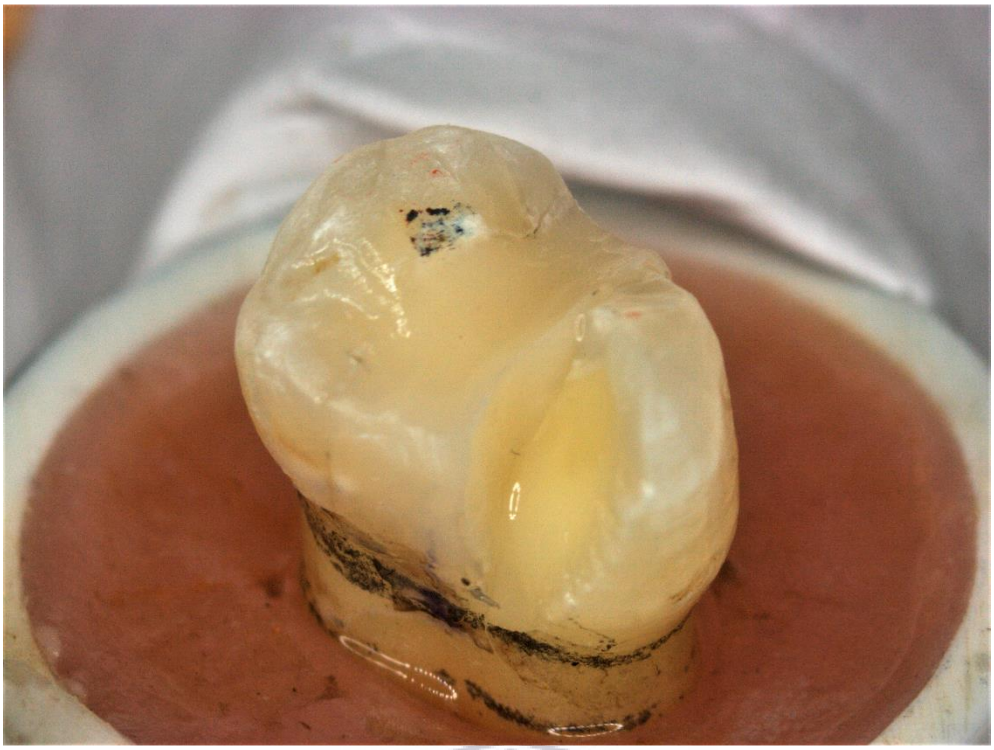

Figure 4.8: Example of tooth without HGFP, cohesive failure.

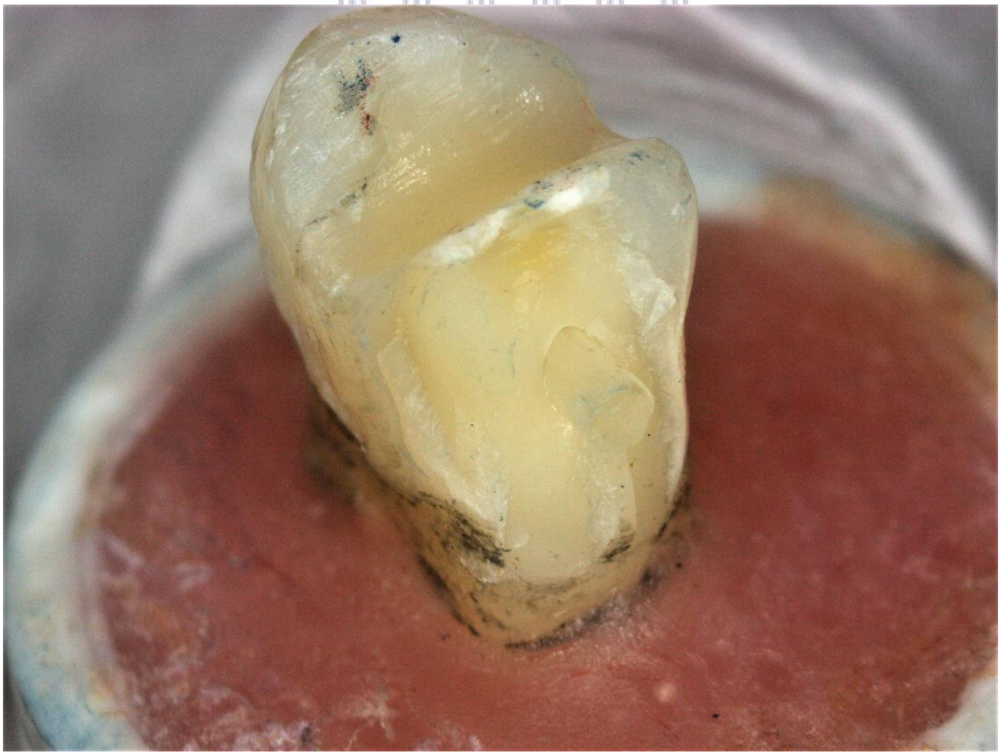

Figure 4.9: Example of tooth with HGFP, cohesive failure.

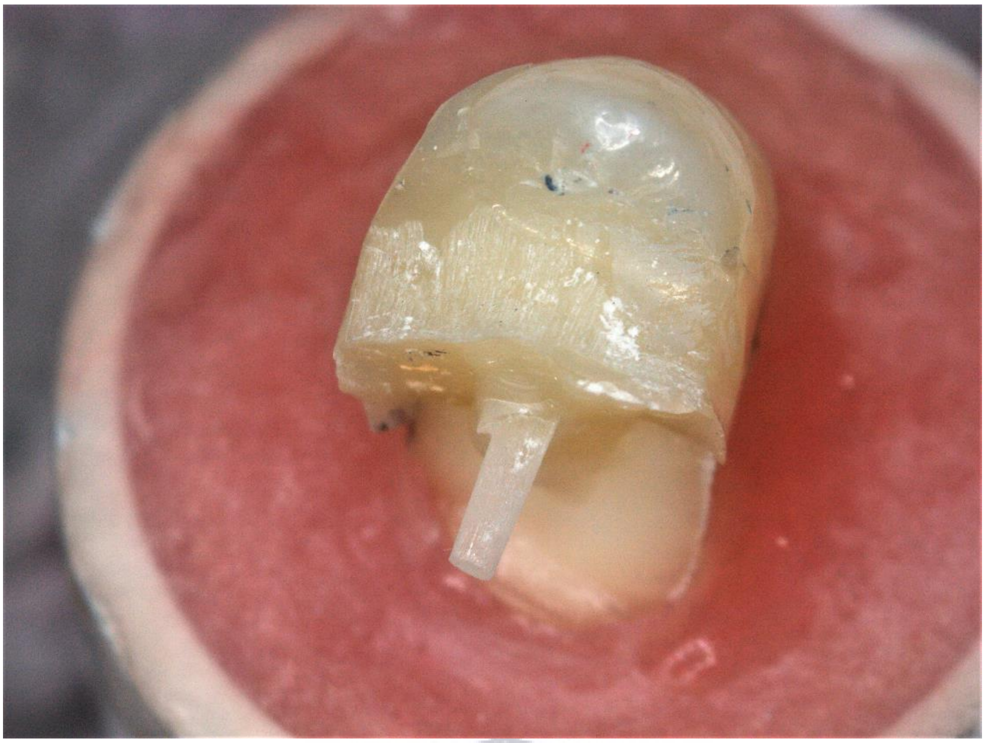

Figure 4.10: Example of tooth with HGFP, adhesive failure.

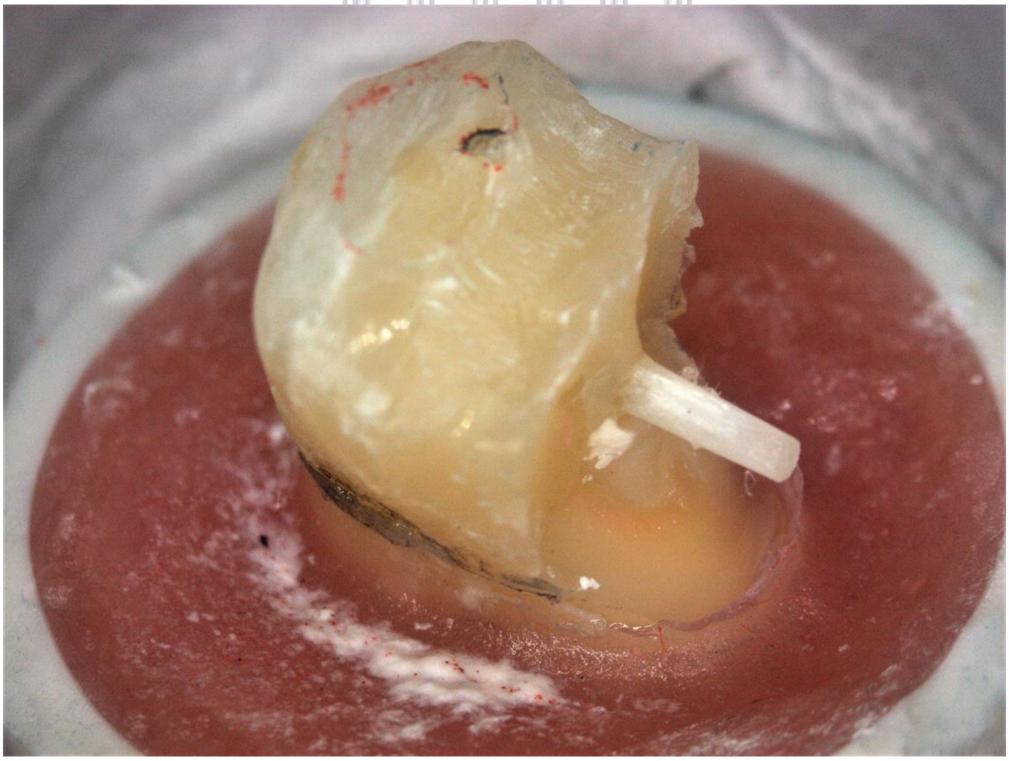

Figure 4.11: Example of tooth with HGFP, adhesive failure.

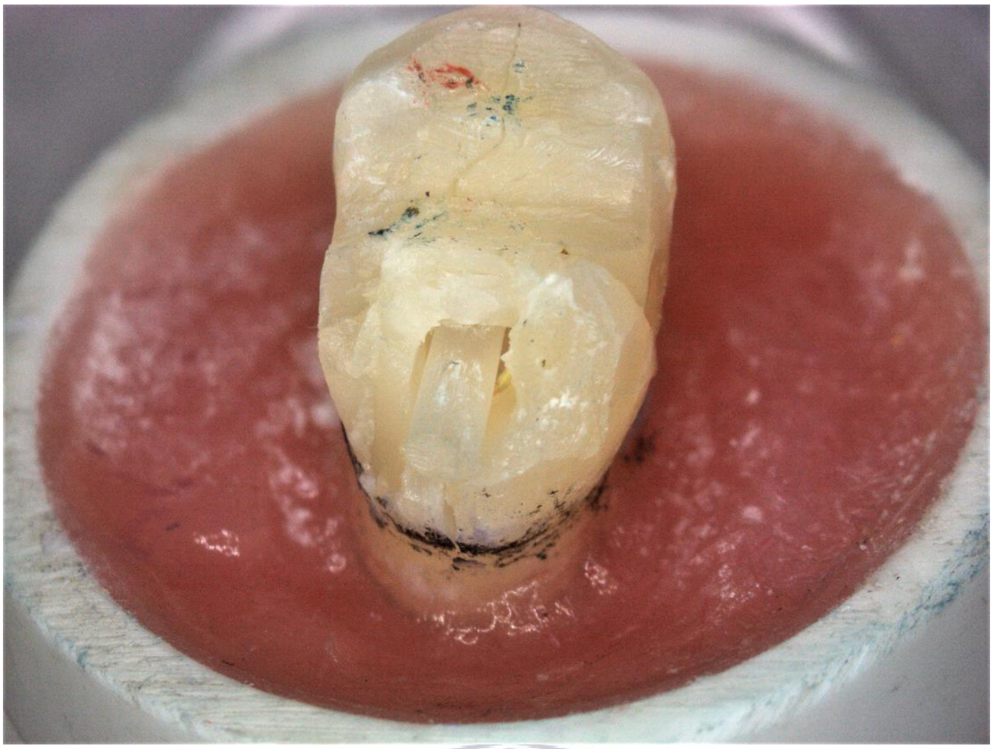

Figure 4.12: Example of mixed failure.

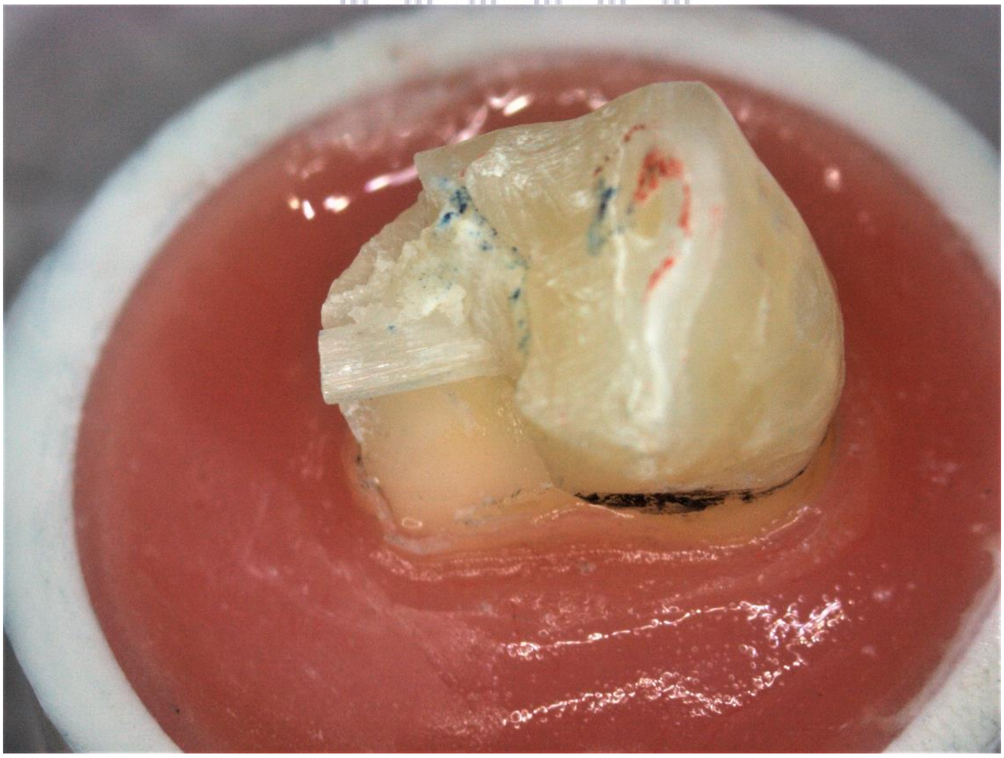

Figure 4.13: Example of mixed failure.

4.1.5 Fracture resistance

The mean fracture resistance in Newton and standard deviations are shown in Table 4.5. The values ranged from 758.4 (294.3) N to 1119.1 (384.3) N. G 3 exhibited the lowest fracture resistance, and the highest is G 6, followed by those of G 5, G 4, G 1, and G 2. With regards to the resistance of fracture, Two-way ANOVA showed the interaction effect between HGFP and sealer types was not significant (P = 0.301). However, the effect of HGFP independently was significant (P = 0.029), while the effect of root canal sealer types independently was not significant (P = 0.561) (Table 4.6). Thus, the insertion of HGFP significantly increased the fracture resistance. Whereas the root canal sealer types did not significantly affect the fracture resistance (P>05).

A T-test revealed a statistically significant difference between groups without HGFP and groups with HGFP (P < 0.028). Groups with HGFP showed higher fracture resistance than groups without HGFP (Table 4.7).

A One-way ANOVA test revealed no statistically significant difference of fracture resistance based on the different types of root canal sealer (P = 0.656) (Table 4.8).

Table 4. 5: Mean fracture resistance (N), Standard Deviation values for all groups

Groups	Mean ± Standard Deviation	Minimum	Maximum
G1 AH sealer	827.00 (296.87)	445	1259
G2 TotalFill sealer	764.88 (285.98)	314	1152
G3 BioRoot sealer	758.40 (294.37)	550	1463
G4 AH sealer with HGFP	879.70 (236.62)	499	1346
G5 TotalFill sealer with HGFP	911.33 (325.59)	390	1400
G6 BioRoot sealer with HGFP	1119.11 (384.36)	555	1582

Table 4.6. Two-Way ANOVA for fracture resistance based on HGFP and sealer types

Source	df	Sum of Squares	Mean Square	*F*	*P*
Sealer type	2	109381.169	54690.584	0.584	0.561
HGFP	1	476108.724	476108.724	5.088	0.029*
Sealer* HGFP (Interaction)	2	230362.371	115181.186	1.231	0.301
Error	49	4585020.278	93571.842		
Total	55	47558817.000			

Table 4.7: T test of fracture resistance based on HGFP

Fracture resistance		N	Mean	Standard Deviation	Mean difference	95% CI Lower	95% CI Upper	P-Value
Groups	Without HGFP	27	780.89	282.536	-185.933	-350.793	-21.072	0.028*
	With HGFP	28	966.82	324.679				

Table 4.8: One-way ANOVA test of fracture resistance based on the type of root canal sealer

Sealer types	N	Mean	Standard Deviation	P-value
AH sealer	18	856.28	258.186	0.656
TotalFill sealer	19	838.11	306.679	
BioRoot sealer	18	929.26	378.454	

4.2 FEA results

The models analyzed in FEBio were post-processed in PostView – which is a part of the FEBio suite.

200 N loading

The maximum Von Mises stresses as well as the stress distribution maps for the two models' surfaces are shown in (Figure 4.14).

The stress distribution in the restored model without HGFP showed that the highest stress concentration was observed at the interface composite and tooth structure (at the occlusal level of the outer model surface) (Figure 4.15). There was also a small area of stress concentration at the palatal cervical region of the tooth as well as in the palatal wall (Figure 4.14).

The stress distribution in restored model with HGFP showed a small area of stress concentration on the occlusal aspect of the buccal and palatal cusp (Figure 4.15). There was no stress concentration visible at the HGFP (Figure 4.16). While the stress distribution patterns were similar for both models, the model with HGFP had lower stress compared to the model without HGFP.

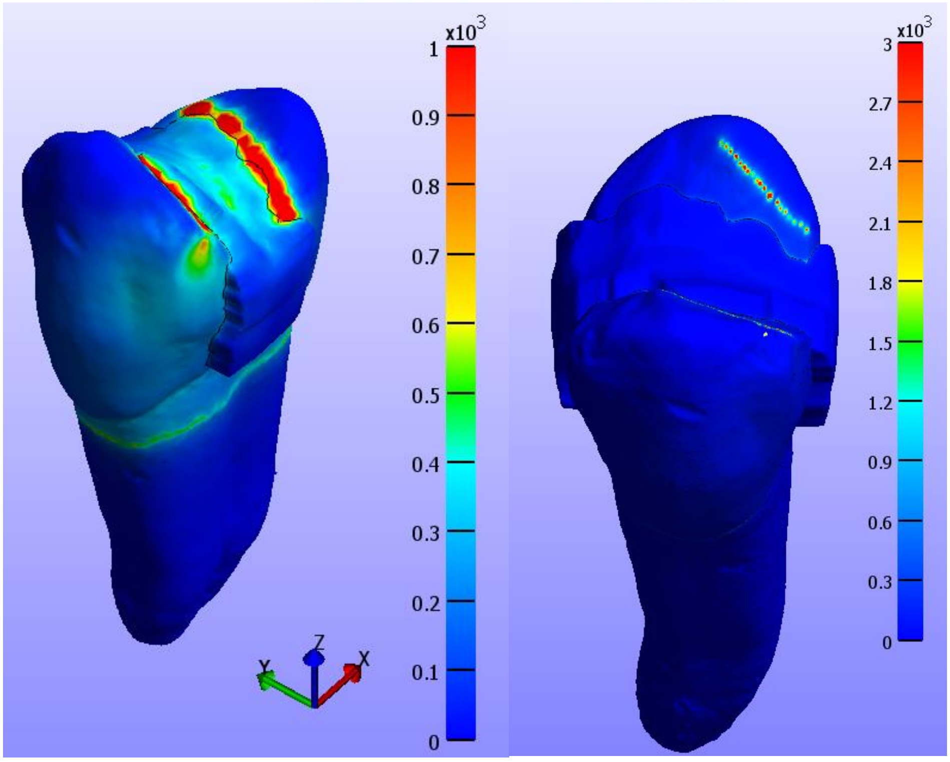

Figure 4.14: Palatal view of stress distribution, model without HGFP (left) and model with HGFP (right)

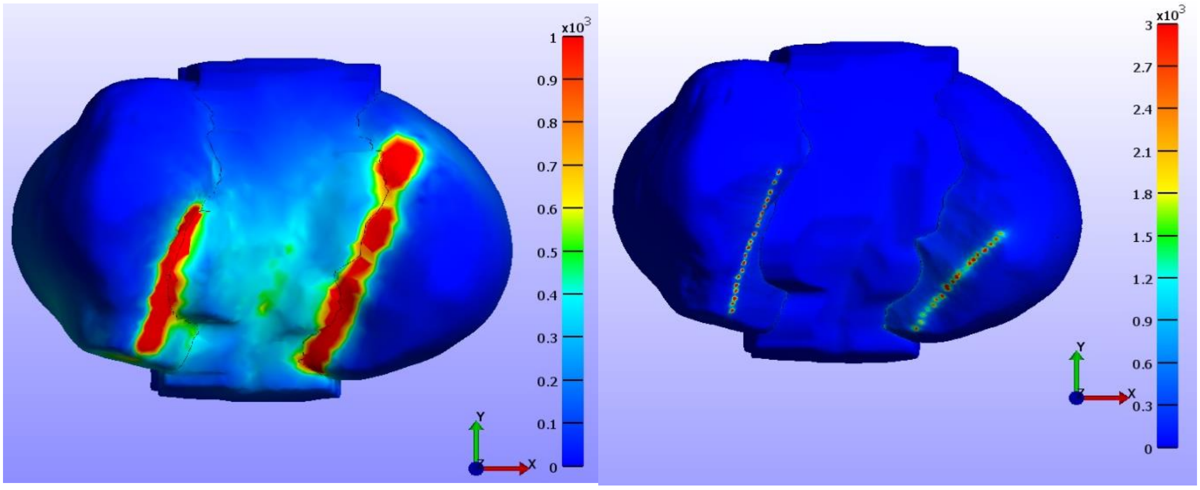

Figure 4.15: Occlusal view of stress distribution, model without HGFP (left) and model with HGFP (right)

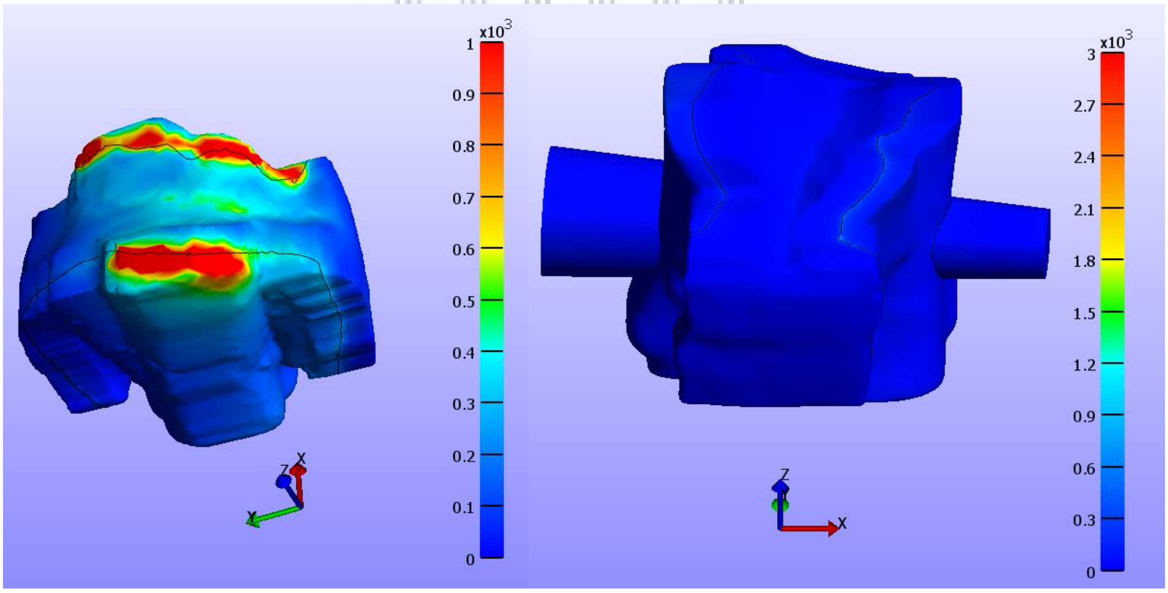

Figure 4.16: view of stress distribution for the composite and the fiber post, model without HGFP (left) and model with HGFP (right)

800 N loading

For the restored model without HGFP, the application of an 800N static load produced extensive areas of stress concentration on the occlusal aspect as well as on the palatal cusp. Another area of high stress was observed in the cervical region of the tooth (Figures 4.17 and 4.18).

The stress distribution in the restored model with HGFP showed that the highest stress was concentrated on the buccal and palatal cusp and at the occlusal interface between the restoration and tooth (Figures 4.17 and 4.18). However, the stresses were lower compared to the model without HGFP. In addition, lower stress concentrations were observed at the cervical region. The mesiodistal view showed that stress is lower in the cervical region as compared to the model without HGFP (Figure 4.17).

The palatal view of both models presented greater stress on the palatal wall compared to the buccal wall (Figure 4.19). Also, it can be noticed that in the restored model without HGFP, the cervical stresses were concentrated at the CEJ and extended apically, whereas, in restored model with HGFP, the cervical stresses were concentrated well close to CEJ only (Figure 4.17 and 4.19). No stress concentration at the HGFP (Figure 4.18).

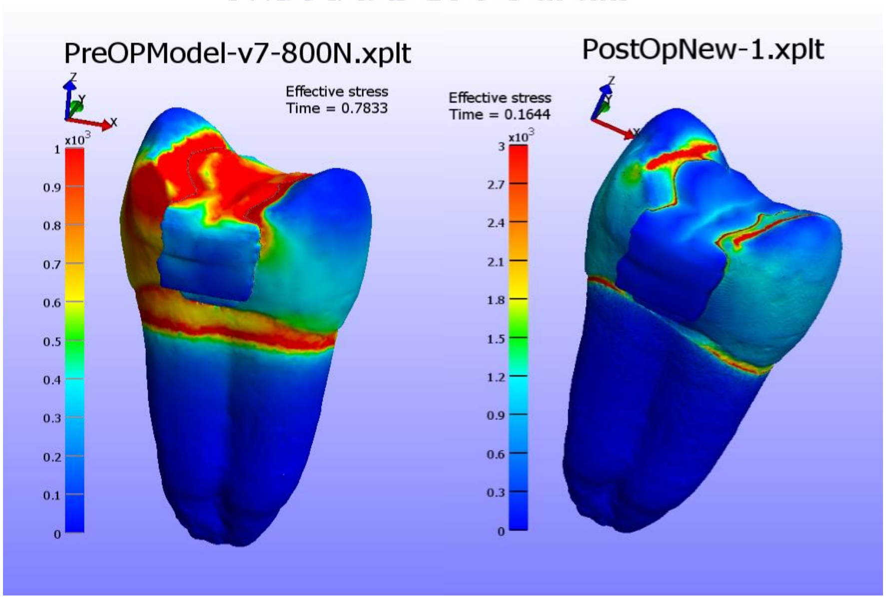

Figure 4.17: External view of stress distribution, model without HGFP (left) and model with HGFP (right)

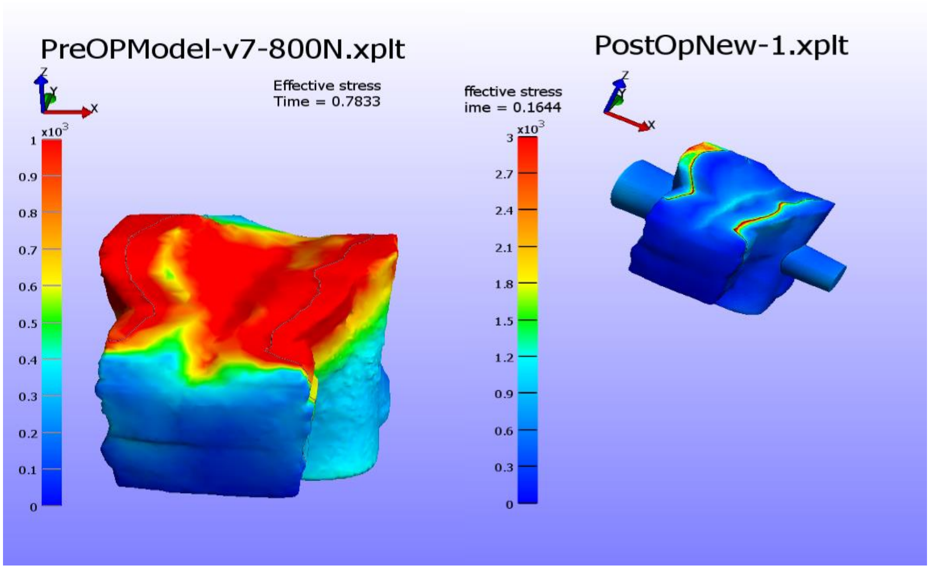

Figure 4.18: view of stress distribution for the composite and the fiber post, model without HGFP (left) and model with HGFP (right)

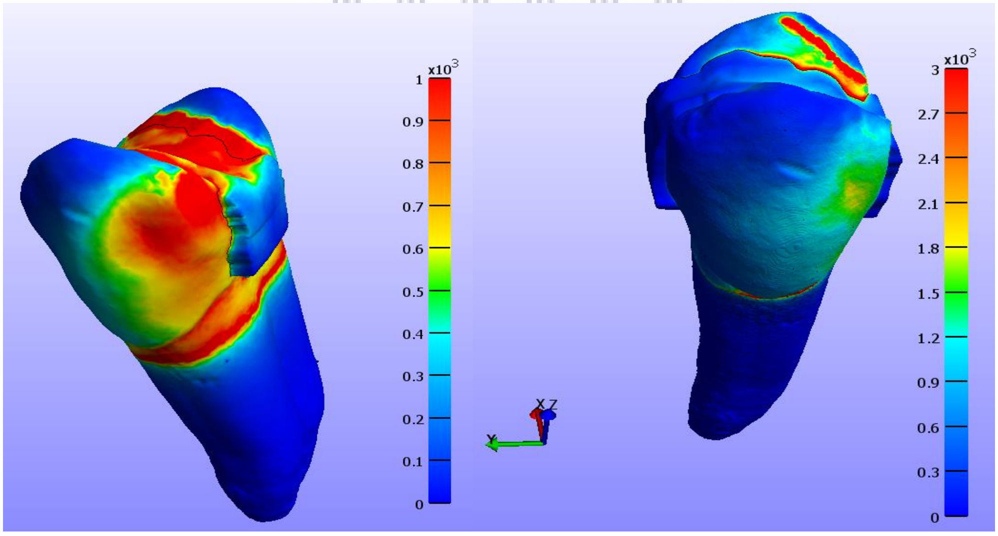

Figure 4.19: Palatal view of stress distribution, model without HGFP (left) and model with HGFP (right)

It should be noted that the range of the color bar for the restored model without HGFP goes from 0-1000 and 0-3000 for the model with HGFP. While the range is different for the two models, both these ranges represent an identical physical stress range as outlined below:

In building the two models in MIMICS/3-Matic from the CT sections, the physical length of 1 mm was represented by 60 length units for the restored model without HGFP model and 20 length units for the HGFP model. This difference in length units during the model building process results in the stress unit of 1 MPa being equivalent to 16.66 and 50 stress units in FEBio. The input of all the forces and elastic properties were scaled and input for analysis to reflect this difference. Consequently, the range of 1-1000 and 1-3000 for the without HGFP and HGFP models are equivalent to the same physical stress unit of 0-60 MPa.

Chapter 5: Discussion

5.1 Discussion of in vitro project

5.1.1 Introduction

Selection of the appropriate restoration for ETT is quite challenging for clinicians and still a highly debatable subject (Vire, 1991; Morgano *et al.*, 1994). While indirect restorations by means of full coverage appear to be a gold standard, these restorations are often invasive and expensive. The movement towards minimally invasive dentistry makes researchers and clinicians explore reliable alternatives to full coverage of ETT.

To the best of our knowledge, no single study has been conducted to evaluate the effect of HGFP on fracture strength of MOD cavity of upper premolars neither by using FEA nor by comparing different types of root canal sealers. This makes our study innovative and unique and will be a valuable addition to the current body of knowledge.

It's been proposed that the composite restoration's adhesive nature strengthens the remaining tooth structure by distributing stress along with the bonding interface, increasing fracture resistance. As such, an intra-radicular post in MOD cavity might have no benefits on the outcome of fracture resistance (Mohammadi *et al.*, 2009; da Rocha *et al.*, 2019). However, HGFP has been proposed to provide some sort of cuspal protection. Therefore, the aim of the present study was to investigate a direct restorative technique that is less invasive by attempting to provide cuspal protection by means of a HGFP.

Despite its limitations, *in vitro* fracture testing is a common experimental method for evaluating the fracture resistance of various restorative options, techniques and materials prior to applications in a clinical environment. While *in vitro* testing does not predict clinical performance, it may provide a preliminary understanding of the potential strengths or weaknesses of new techniques and procedures as compared to existing ones before introducing them in a clinical setting (Amaral *et al.*, 2007; Naumann *et al.*, 2009). Since the introduction of a HGFP for cuspal protection of premolars is still a relatively newly introduced procedure, *in vitro* investigation for this technique is still relevant prior to taking it to the clinical setting. In addition, the fact that this research project was performed using a methodology incorporating both thermocycling and dynamic loading is providing additional evidence that is lacking in all other studies (except 1) performed on HGPF applications for ETT.

Different root canal sealers were also used to assess their possible influence on fracture resistance and fracture pattern of ETT with MOD cavities restored with direct adhesive composite material.

The first null hypothesis of this study was that the HGFP would not affect the fracture resistance or fracture pattern in maxillary ETP with MOD cavities restored with direct CR. This hypothesis was rejected.

The second null hypothesis was that the type of root canal sealers would not affect the fracture resistance or fracture pattern in maxillary ETP with MOD cavities restored with direct CR. This hypothesis was accepted.

5.1.2. Methods

1. Selection of the specimens and cavity preparation

Upper RCT premolars with MOD cavities were chosen because they present an unfavorable anatomic shape, crown volume, and crown/ root proportion, making them more susceptible to cusp fractures than other posterior teeth when submitted to occlusal load (Soares *et al.*, 2008c). In addition, upper premolars are subjected to more shear forces than molars during mastication, which is a combination of occlusal and lateral forces, making them particularly prone to fracture (Oskoee *et al.*, 2009). Furthermore, clinical observation studies have shown that maxillary premolars are more prone to fractures (Testori *et al.*, 1993; Fennis *et al.*, 2002).

It was decided to include MOD cavity preparations in the experimental design because it has been shown that root canal access preparations alone had little effect on tooth strength and fracture resistance (5%), whereas MOD cavity preparation did (63 %) (Reeh *et al.*, 1989b). In addition, premolars requiring endodontic treatment may have a pre-existing structural breakdown due to decay or defective restorations. MOD cavity preparations usually lead to formation of long cusps (The cusp's length and deflection increase with deeper cavity preparations). Thus, there is a need for a restoration that replaces the tooth structure and increases the fracture resistance of the remaining tooth and promotes effective marginal sealing (Monga *et al.*, 2009).

A parallelometer was used to standardize the seating of every tooth in the plastic tubing with its long axis parallel to the vertical axis of the tube. This also ensured a standardized positioning of all specimens in the chewing simulator as well as in the universal testing machine. The parallelometer was consequently modified to mount a handpiece so that the drill was positioned parallel to the long axis of the tooth to ensure a standardized preparation of cavities with their occluso-gingival dimension parallel with the long axis of the tooth.

2. Selection of materials

GFP were chosen because of their low modulus of elasticity, similar to dentin, so that they can transfer the load forces equally along the root (Schwartz and Robbins, 2004; Tang *et al.*, 2010). In this study, the GFP was placed in a horizontal direction through buccal and palatal walls; this method was reported to improve ETT resistance to fracture (Karzoun *et al.*, 2015) and reduce unrepairable fracture (Mergulhão *et al.*, 2019).

The fracture resistance of ETT has been shown to be higher with adhesive CR restorations than non-adhesive ones (Hürmüzlü *et al.*, 2003; Siso *et al.*, 2007; Soares *et al.*, 2008c). This is because CR restorations adhere to the tooth structure, strengthening the tooth and providing an alternate restorative approach to cuspal coverage.

The present study restored the MOD cavities with Nano Hybrid universal CR Filtek Z250 XT, which contain high filler loading (81.8 wt.%, 67.8 vol.%). Besides, Filtek Z250 XT has silica/zirconia clusters “nanoclusters” with an average filler size of 0.1-10 microns and 20 nm surface-modified silica. Higher filler loading could reduce the volumetric shrinkage and minimize the shrinkage stresses in resin-based composite (RBC). This was due to a decrease in resin content, which in turn reduced the amount of shrinkage (Ferracane, 2005). Moreover, using a low-shrinkage composite significantly enhances the strength of upper premolars when subjected to compression loadings (Hamouda and Shehata, 2011). The high mechanical properties may be due to the presence of nanocluster that improves withstand to damage and increases the durability of nanocluster CR restorations (Yang *et al.*, 2003; Curtis *et al.*, 2009a). Incorporating nanoclusters particles into a conventional resin matrix may alter the ensuing failure mechanisms and give enhanced damage tolerance unique to reinforced nanoclusters (Curtis *et al.*, 2009b).

The usage of the PDL has particularly been controversial in the literature**.** Hence, PDL simulation was not used in this study because several studies have shown that PDL did not affect fracture strength under these conditions of testing (Taha *et al.*, 2011; Marchionatti *et al.*, 2014; González-Lluch *et al.*, 2016; Tian *et al.*, 2019; Nawafleh *et al.*, 2020; Zheng *et al.*, 2020). In addition, it was found that the PDL properties do not significantly influence the validity or the outcomes of the FEA studies (Provatidis, 2000). Furthermore, a recent meta-analysis revealed that PDL simulation did not influence the fracture strength test (Gaeta *et al.*, 2021).

Gutta Percha with AH sealer is the gold standard materials for root canals obturation (Apicella *et al.*, 1999). In the current study, the root canals of maxillary premolars were filled with different root canal sealer systems, one AH sealer and two recent types of bioceramic sealers (TotalFill BC sealer and TotalFill BC Points, BioRoot™ RCS sealer). Previous studies have shown that bioceramic-based sealers significantly increased the fracture resistance of ETT (Ghoneim *et al.*, 2011; Topçuoğlu *et al.*, 2013; Patil *et al.*, 2017). In contrast, several studies found that bioceramic-based sealers did not improve the fracture resistance of teeth (Sağsen *et al.*, 2012; Dibaji *et al.*, 2017; Almohaimede *et al.*, 2020).

3. Selection of laboratory equipment

Thermal cycling appears to be a valid laboratory method to accelerate the aging of restorative materials (Amaral *et al.*, 2007). Despite this aging method being the most widely used and cyclic loading, there is a lack of a standardized protocol (Morresi *et al.*, 2014). Many researchers who employed the ISO standard protocol (500-cycle system) found that thermocycling has no effect on the adhesive system's bond strength (Gale and Darvell, 1999; Li *et al.*, 2002; Dos Santos *et al.*, 2005). It has been documented that thermocycling stresses the bond between the resin and tooth structure in addition to its effect on the bond strength (depending on the used adhesive system) (El-Araby and Talic, 2007); In addition, thermocycling can cause microleakage, probably due to its effect on the marginal integrity of the restoration (Cenci *et al.*, 2008). In this regard, a study by Miyazaki *et al.* (1998) found that a regimen of 30,000 cycles reduces the bond strength. This finding supports the negative effect of thermocycling on the restorative interface after many cycles. Such finding also suggests that "water" might be the key factor accelerating the aging process during thermocycling (Aguilar *et al.*, 2002).

Several studies conducted to investigate fracture resistance of restorations of ETT used only static load (de V Habekost *et al.*, 2007; Cubas *et al.*, 2011; Taha *et al.*, 2011; Karzoun *et al.*, 2015; de Assis *et al.*, 2016). The clinical relevance of the static load to failure approach is doubtful because the applied load is usually considerably higher than the natural biting force. The alternative to static load is fatigue testing which represents physiological mastication and fatigue failure behaviour of teeth or/and restorations. Cyclic fatigue might result in severe effects on fracture strength more than a static load due to cracks initiation and propagation within restorations and tooth structure (Stappert *et al.*, 2006; ElAyouti *et al.*, 2011). Fatigue fracture can happen at the point of highest stress, which is the interface between the tooth and the restoration (Soares *et al.*, 2008a).

The number of cycles varied widely among studies varying from 1000 to 8000 (Carrilho *et al.*, 2004), 50,000 (Frankenberger and Tay, 2005; Mergulhão *et al.*, 2019), 100,000 (Lin and Drummond, 2010), 200,000 (Carrera *et al.*, 2017), and up to 1,200,000 cycles (Kern *et al.*, 1999; Dere *et al.*, 2010; Guess *et al.*, 2013), which is equivalent to five years of clinical performance (Kern *et al.*, 1999). In the present study, ETT were subjected to cyclic loading 50000 times before the fracture test to simulate oral chewing function. This is a lower number of cycles than reported in other studies. However, this study also used a force sensor mounted on the antagonist so that a constant force could be monitored at the tooth-antagonist interface. Hence, cyclic loading could only be performed one tooth at a time. Cyclic loading of one tooth required 14 hours. For 60 teeth, cyclic loading alone required a total of 840 hours or 35x24hr-days. Applying 50,000 cycles simulated approximately three to 12 months of clinical service (Wiskott *et al.*, 1995).

4. Selection direction of loads

In the present study, the teeth were loaded in a vertical direction parallel to the longitudinal axis on both buccal and palatal cusps. Because of the standardized methodology used for mounting the teeth in the plastic tubing using a surveyor, preparing the cavity again using a handpiece mounted on a surveyor, the contact points of the antagonist of the chewing simulator and the static tester on the occlusal surface of the teeth were the same. Occlusal contact points were on the cuspal inclines simulating a physiological occlusion and to obtain a degree of non-axial loading (Salameh *et al.*, 2006). This is in line with the previous studies (Wendt *et al.*, 1987; Reeh *et al.*, 1989a; Soares *et al.*, 2008d; Karzoun *et al.*, 2015; Atalay *et al.*, 2016; Göktürk *et al.*, 2018; Mergulhão *et al.*, 2019). In other studies, an oblique load (45° to the long axis of the tooth) was applied on the buccal cusp (Taha *et al.*, 2011; Taha *et al.*, 2014; Taha *et al.*, 2017). Other studies applied the loads on a palatal cusp (Bajunaid *et al.*, 2020; Scotti *et al.*, 2020) or at tooth- restoration interface (Trope *et al.*, 1986; Hernandez *et al.*, 1994; Hürmüzlü *et al.*, 2003).

5.1.3. Results

The results of this *in vitro* study indicate a promising effect of HGFP in strengthening the ETP. The use of HGFP in ETP resulted in a significant reduction of unrestorable catastrophic fractures as well as an increase in the fracture resistance of ETT. This is in agreement with studies that revealed that the extension of a HGFP through the buccal and palatal walls strengthens the CR restoration and, through adhesion, strengthens the cusps, increases the fracture resistance of ETP (Karzoun *et al.*, 2015; Ferri *et al.*, 2021) and reduces unrestorable fractures (Mergulhão *et al.*, 2019; Ferri *et al.*, 2021).

Further evidence can be obtained from the Beltrão *et al.* (2009) and Favero *et al.* (2015) studies. They found a significant increase in fracture resistance when insertion of a HGFP within the direct composite restoration of endodontically treated molars. Moreover, the Bromberg *et al.* (2016) and Bainy *et al.* (2021) studies advocated that HGFP with CR enhances fracture resistance of endodontically treated molars. Contrarily, studies by Soares *et al.* (2008c) and Mohammadi *et al.* (2009) concluded that glass fibers posts did not strengthen the ETP. An explanation for this could be that they used the fiber post intra radicular inside the root canal.

Given the above evidence on the effectiveness of HGFP regarding the strengthening of ETT, and given that HGFP groups in our study has more efficacy than groups without HGFP in regard to reduction of unrestorable catastrophic fractures as well as increased fracture resistance, it can be suggested that the use of HGFP with CR in MOD cavities can be considered as a promising approach for clinical application.

Regarding the fracture patterns, in the current study, the groups with HGFP showed a significantly more restorable fracture compared with groups without HGFP, which is in agreement with the findings of other studies (Aslan *et al.*, 2018; Bahari *et al.*, 2019; Mergulhão *et al.*, 2019; Bainy *et al.*, 2021; Ferri *et al.*, 2021). In contrast, a study by Karzoun *et al.* (2015) which used HGFP with upper premolars showed more unrestorable fracture. One study by Bromberg *et al.* (2016) using HGFP with molars showed more unrestorable catastrophic fractures. The variability could explain the differences of findings across different studies in defining the fracture location by different studies; for example Karzoun *et al.* (2015) uses the cervical third of the root, Bromberg *et al.* (2016) define it as a fracture in the pulpal floor, and Mergulhão *et al.* (2019) uses "simulated bone level."

There is growing evidence that intraradicular placement of post to strengthen the dental structure has already been reported to be ineffective (Soares *et al.*, 2008a; Mohammadi *et al.*, 2009; Barcellos *et al.*, 2013; da Fonseca *et al.*, 2018; da Rocha *et al.*, 2019). Further, post-space preparation led to significant tooth root weakening. Additionally, during post-space preparation, procedural errors may arise. Although not very common, perforations in the apical part of the root or the lateral mid-root wall of a "strip-perforation" can be included in these accidents. Placing posts may further increase the likelihood of root fracture and treatment failure (Schwartz and Robbins, 2004).

Regarding failure mode, the most predominant observation noted in our study was tooth cohesive failure, which was recorded at 40%, then mixed failure 35%, and adhesive failure 25%. Concerning adhesive failure, it was proposed that high compressive strength materials are shown to withstand strong loads, especially when utilized as posterior restorations (Lien and Vandewalle, 2010). Further, fracture toughness shows the material's capacity to be plastically deformed without fracture, as well as its resistance to crack propagation (Sakaguchi and Powers, 2012). Therefore, Filtek Z250 XT (resin composite used in this study) may have a higher resistance to crack propagation, so the fracture happened at the weakest bond, the interface between tooth and composite. All teeth in adhesive failure showed debonding at the tooth-restoration interface at the palatal margin, the crack initiated at palatal-occlusal line angle. Then all cracks propagated obliquely to the palatal root surface and caused a deflection of the tooth wall, which resulted in palatal wall fracture. The similarity in adhesive failure mode indicates that failure happens in two stages: first, debonding occurs at the palatal interface between the cavity wall and restoration. Second, following debonding, the palatal cusp acts as a cantilever beam and fractures in the same manner. The palatal cusps were involved in all adhesive failures (type II). The palatal cusps are the functional cusps for upper premolars and have a lower volume of tooth structure than the nonfunctional ones buccal cusps; they are more prone to fracture. (Khera *et al.*, 1990). Failure modes have varied between studies based on tooth mounting as well as the direction and location of occlusal loading (Reeh *et al.*, 1989b; Soares *et al.*, 2008c).

A study conducted by Taha *et al.* (2011) reported the adhesive failure predominantly at the buccal interface, with cuspal fracture propagated obliquely from the buccal line angle of the occlusal floor, which could be explained by the fact that an oblique load was applied to the buccal cusp. Noteworthy, in our in vitro study, cohesive failure of tooth structure recorded the highest percentage (40 %) of all failure modes, and this is consistent with results reported by Mondelli *et al.* (2007), Atalay *et al.* (2016) and Issa *et al.* (2018). This may be due to the applied load was stress to tooth structure directly. In contrast, cohesive failure of the restorative material (isolated failure of restoration) never occurred within the restorative material itself. This result agrees with the studies by several groups (Wendt *et al.*, 1987; Ausiello *et al.*, 1997; Atalay *et al.*, 2016; Ismail and Abd-alla, 2020). This may be due to the fact that Filtek Z250 XT (CR used in this study) is characterized by high compressive strength and fracture toughness.

Concerning the effect of root canal sealer types on the fracture resistance of ETT, BioRoot sealer groups showed superior than other sealers, although the differences were not statistically significant; the mean fracture of BioRoot sealer was 929.26 N while the mean fracture were 856.28 N and 838.11 N for AH sealer and TotalFill sealer respectively. This finding is in accordance with Guneser *et al.* (2016), Gervini *et al.* (2018), İnce Yusufoglu *et al.* (2019), Saba and ElAsfouri (2019); Uzunoglu Ozyurek and Aktemur Turker (2019) and Almohaimede *et al.* (2020). Despite the majority of the studies found that the use of endodontic sealers increased the fracture resistance of ETT, there was inconclusive evidence found for the reinforcing impact of resin-based sealers and calcium silicate-based sealers (Uzunoglu-Özyürek *et al.*, 2018). Camilleri (2015) has reported that bioactivity and adherence of BioRoot RCS to canal walls may be enhanced by calcium hydroxide formation during early setting. Hence, the increased fracture resistance of BioRoot RCS reported in our study could be explained by biomineralization activity, which interacts with this sealer with root canal walls.

5.2 Discussion of FEA part

As a numerical simulation technology, FEA offers various advantages: better control of the test conditions and reducing errors that might arise during laboratory work. The strength of FEA studies lies in assuming constant conditions for all the investigated models. FEA is a useful supplementary protocol for fatigue testing used in dentistry (Ausiello *et al.*, 2002; Al-Omiri *et al.*, 2011). It can also help identify the pattern or location of stresses in a structure rather than just providing the maximum load, load at fracture, or the resulting fracture pattern, which is the case in fracture resistance laboratory studies. This study aimed to compare stress distribution between models rather than to quantify stress values. To the best of our knowledge, the influence of HGFP placed in MOD cavity with a CR to restoring ETP has not yet been studied using the FEA method. Hence this is an innovative aspect of this research project.

The third hypothesis of this study was that HGFP does not affect the stress distribution in maxillary ETP with MOD cavities restored with CR. This hypothesis was rejected.

In the present study, two models were created to simulate the mechanical testing; the first model consisted of restored MOD maxillary premolar without HGFP, and the second consisted of restored MOD maxillary premolar with HGFP. PDL was not created for both models to simulate the mechanical testing conditions. It has also been noted that the PDL properties do not significantly influence the validity or the results of the FEA studies (Provatidis, 2000). The two models were subjected to two loads: 200 N, which is the normal biting force of maxillary premolars, and 800 N, which was roughly what the specimens failed in the mechanical testing (780 N group without HGFP and 966 N group with HGFP). This is a consistent with the results of Jantarat *et al.* (2001), who reported the normal biting force for upper premolars ranged between 100–300 N. However, higher biting forces must be expected in patients with functional disorders like as clenching or bruxism, whose biting forces varied from 520 to 800 N (Nishigawa *et al.*, 2001; Rahman *et al.*, 2016). A recent scoping review of finite element models of premolars found the loading varied greatly across the studies ranging between 100 N to 2000 N (Richert *et al.*, 2020). All materials used in this study were homogenous, isotropic, and linearly elastic, except the HGFP that is orthotropic.

According to the current study's findings, the concentration of Von Mises stress was highest in the occlusal areas of both models and loads. The highest stresses were found at the occlusal interface between tooth and restoration; the highest Von Mises stresses seemed concentrated at the tooth-composite interface. This finding might indicate that the interface between tooth and restoration is crucial for fracture propagation from the coronal portion of the tooth. Notably, the model with HGFP showed less stress concentration on the occlusal surface than with the model without HGFP. This implies that HGFP reduced the maximum von Mises stresses on the occlusal surface and optimized the stress distribution in the same areas. In addition, the von Mises stress concentration was highest at cervical regions for both models. Interestingly, in restored model without HGFP, the cervical stresses were concentrated at CEJ and extended apically, whereas in restored model with HGFP, the cervical stresses were concentrated close to CEJ only. This observation means that HGFP is capable of reducing stress concentration at cervical regions (stress relieving). It may also explain the observation in experimental testing that the groups with HGFP showed a significantly more restorable fracture pattern and reduced catastrophic fractures compared with groups without HGFP.

Another interesting finding that can be seen from the current study is that von Mises stresses were significantly lower throughout the whole model with HGFP, and better stress distribution was observed in the model with HGFP.

It was found that the stresses in HGFP model were located above the bone level while in the model without HGFP located below the bone level and extended apically. These results are consistent with the findings reported previously for intra radicular posts (Kumar and Rao, 2015; Madfa *et al.*, 2015; Chieruzzi *et al.*, 2017; Lee *et al.*, 2017; Ibrahim *et al.*, 2021).

When fiber posts are used, the theory of positive stress redistribution aside from the cervical radicular dentin appears to be consistent with the findings of an earlier in vitro research by Sorrentino *et al.* (2007) that revealed that ETP with MOD restorations and fiber posts frequently had restorable failures, while specimens restored without posts had a prevalence of non-restorable, subgingival fractures. In addition, a recent study reported using an FEA that the resistance of upper premolars restored through fiber post with MOD cavity allows a positive distribution of occlusal forces; preventing dangerous stress concentration (Zarow *et al.*, 2020). In contrast, A FEM study on endodontically treated upper second premolars showed whether a post is present or not, the stress concentrations at the cervical region are dominant (Al-Omiri *et al.*, 2011).

The findings of FEA simulation predict the tooth fracture at the 800N load; this agrees approximately with the mechanical test that resulted in a 780 N mean fracture load for the restored model without HGFP and 966 N mean fracture for the model with HGFP.

FEA results showed that HGFP reduced the stress concentration at the occlusal interface and cervical region compared with the model without HGFP. In contrast to our results, a recent FEA study reported that the use of transfixed GFP does not help to reduce the stresses in endodontically treated molar (Borges *et al.*, 2021). This difference may be due to the fact that our study used one HGFP with a maxillary premolar model, whereas that study used two transfixed GFP with a molar model. The presence of two holes on the tooth wall might have negatively affected the teeth' stress distribution and fracture resistance.

The highest stresses were found on occlusal areas and at the cervical region of the palatal part of the crown. This is in agreement that the most common failure mode of upper ETP with MOD cavities restored with CR is the fracture of the palatal wall of the tooth (Deliperi *et al.*, 2005; Lin *et al.*, 2008).

Furthermore, the use of von Mises' stress criterion is one strength that must be considered. In brief, it is a scalar stress measure; simply it combines compressive, tensile, and shear stress components with the aim to identify the more areas of the model that are prone to the fatigue as a result of being under the highest stress. Accordingly, we decided to choose this criterion so that comparing the results of our experiment and other studies will be reliable and objective. Some investigators consider the tensile stress component to be the main predisposing factor in tooth fracture (Pierrisnard *et al.*, 2002; Lertchirakarn *et al.*, 2003). However, the Von Mises stresses indicate the most highly stressed areas as they are more representative of a multiaxial stress state. The latter is considered an accurate predictor of fatigue failure (Pierrisnard *et al.*, 2002; Lanza *et al.*, 2005).

Again, so far, no studies have been carried out to assess the impact of HGFP on fracture strength of MOD cavity of upper premolars neither by using FEA nor by comparing different types of root canal sealers. That is why we believe that our study is novel and contributes to the existing knowledge. Strikingly, the results of FEA support the experimental (*in vitro*) findings and explain how HGFP reinforces the MOD cavity. FEA shows that HGFP reduces the stress concentration and thus reduces the chance of crack forming at the cervical region. It seems that HGFP changes the stress distribution favorably. In fact, FEA is considered a valid method to analyze the results of *in vitro* testing. Compared to the other assessed sealers, BioROOT RCS sealer provided higher fracture resistance irrespective that the differences were not statistically significant.

5.3 Integration of *in vitro* and FEA

While *in vitro* laboratory testing on extracted human teeth is necessary for obtaining meaningful information about fracture load and mode of fracture, they are typically destructive in nature and have limited capacity for investigating the stress-strain relationship in the tooth restoration complex (Alp *et al.*, 2020; Zarow *et al.*, 2020). Therefore, 3D-FEA is an engineering tool that uses mathematical techniques and computer simulation to investigate the mechanical behaviour of complex systems. It can be used in dentistry, medicine, and biology (Scotti *et al.*, 2015).

In this study, ETP with MOD cavity restored with CR and HGFP shows increased incidence of restorable fractures which were correlated with FEA results.

The results of FE simulation in the present study supported the *in viro* results with matching at the fracture point. Furthermore, the FE simulation showed that the palatal portion of the crown region was the most prone to fracture. This result corresponded to the fracture test results, given that all teeth fractured in this area. Overall, the experiment and FEA simulation results showed a good correlation.

5.4 Limitations

- The sample size was small. Larger sample size is encouraged for future studies to confirm the current results.
- Groups included teeth with different dimensions.
- In spite of conflicting opinions, the teeth and FEA models were not surrounded by a simulated PDL.
- The maximum principal stress was not used in the FEA part. The stress values of FEA were also not presented due to challenges and limitations capabilities of the output software program.

- During fracture testing, two specimens failed due to operator error, and due to time constraints, they were excluded from the study.
- Cyclic loading was limited to 50000 cycles due to time constraints.
- Lack of positive control group of sound teeth, and negative control group of prepared but unrestored teeth.

Chapter 6: Conclusion and recommendations

- The insertion of HGFP in MOD cavity with CR increased the fracture resistance of ETP significantly.
- The insertion of HGFP in MOD cavity with CR increased the restorable (repairable) fracture of ETT and reduced non-restorable catastrophic fractures significantly.
- The type of root canal sealers did not affect the fracture resistance or fracture patterns of ETT.
- HGFP exhibited a favourable stress distribution pattern at loading areas and at the cervical region.

Further research:

- Larger sample sizes are encouraged for future studies.
- Further studies with different types of post and composites.
- Further research changing the dimensions of the cavities and the different level position (occluso-gingivally) of the HGFP.
- Further studies by FEA with different types of post and composites.
- Further clinical studies to evaluate the impact of HGFP.

Chapter 7: References

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