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Effect of Preparation Designs on Marginal Adaptation and Fracture Resistance of Endodontically Treated Teeth Restored With Different Composite Materials

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ABSTRACT

The objective was to evaluate the marginal adaptation and fracture resistance of endodontically treated teeth (ETT) restored using various preparation designs and materials. Except for the positive control group ($n = 15$), 135 teeth with ETT were divided into three main groups ($n = 45$): MOD (Mesio-occlusal-distal), retention slots and cuspal coverage. Each main group was further subdivided into three sub-groups ($n = 15$): nano-hybrid composite resin, short fibre-reinforced composite resin (SFRC) and a CAD/CAM nano-ceramic composite block. After chewing simulation, the specimens were examined using SEM; a quantitative marginal adaptation analysis and fracture resistance test were performed. MOD preparations exhibited the highest marginal deterioration ($p < 0.001$). Gingival marginal deterioration in nano-hybrid composite restorations was significantly higher than in CAD/CAM restorations ($p = 0.023$), though the difference between nano-hybrid and SFRC restorations was not significant ($p = 0.447$). The MOD cavity showed significantly lower fracture resistance compared to retention slots and cuspal coverage groups ($p < 0.001$). SFRC demonstrated the highest fracture resistance ($p < 0.001$).

1 | Introduction

Traumatic dental injuries, extensive caries, or inadequate restorative treatments often necessitate endodontic treatment. However, such treatments can negatively impact the long-term prognosis of the tooth due to biomechanical changes, collagen alteration, reduced hardness and loss of hard tissues during cavity preparation [1, 2]. Protecting endodontically treated teeth (ETT) from fractures through reinforcement is crucial [3].

Various restorative techniques and materials, including post-core systems, ceramics, direct composite restorations and both partial and total crowns, have been proposed for ETT [4]. Composite resin restorations have become increasingly popular due to their aesthetic qualities and mechanical advantages, such as adhesion to sound tooth structure, which contributes to increased fracture resistance [5]. However, composite resin systems have some disadvantages, such as polymerisation shrinkage, cuspal deflection, microleakage and marginal staining [6–8].

A newly developed restorative material, called short fibre reinforced bulk-fill composite (everX Posterior, GC Europe, Leuven, Belgium), has shown promise in preventing crack propagation and supporting teeth under occlusal pressure [9]. Only limited data are available to demonstrate its effects on marginal integrity and fracture resistance across different restoration designs.

Due to the large amount of tissue loss in ETT, indirect restorations might be more favourable than direct restorations [10]. Among the materials used in indirect systems, resin composite restorations can serve as a budget-friendly alternative to full ceramic restorations. In comparison to ceramics, composites are generally simpler to fabricate and may result in less wear on adjacent teeth [11]. Nanoceramic composites consist of nano-sized ceramic particles dispersed within a polymer matrix, offering superior strength, wear resistance and aesthetic performance compared to conventional composites. Additionally, their compatibility with CAD/CAM technology allows for the precise fabrication of customised restorations. Due to these advantages, nanoceramic composites facilitate the production of indirect restorations in dentistry, ensuring more aesthetic and consistently high-quality results [12].

In the literature, various preparation techniques were described as means to support weakened tooth tissue, strengthen the coronal structure, and enhance the resistance of ETT against fracture and marginal gap deformation. Different preparation approaches such as 'cuspal coverage' and 'retention slots' with different restorative materials may affect the fracture resistance of ETT with MOD cavities. However, there is limited information on the marginal adaptation and fracture resistance of ETT that have been restored using short fibre-reinforced composite resin (SFRC) and CAD/CAM nano-ceramic composite blocks, specifically in cavities that require cuspal coverage or have retention slots.

The aim of this study was to assess the marginal adaptation and fracture resistance of nano-hybrid composite, SFRC and CAD/CAM composite restorations prepared with cuspal coverage and retention slots in ETT. The first null hypothesis was that no differences would be found in marginal adaptation and fracture resistance among various preparation designs, while the second null hypothesis suggested no differences among the restorative materials.

2 | Materials and Methods

The manuscript of this laboratory study has been written according to Preferred Reporting Items for Laboratory studies in Endodontology (PRILE) 2021 guidelines (Figure 1). This study was approved by the Research Ethics Committee, under report number 15/31. All participants were invited voluntarily, and those who agreed to participate signed an informed consent form that was approved and stamped by the local ethics committee. A total of one hundred and fifty human mandibular molars extracted for periodontal reasons were randomly selected. The teeth were disinfected in 0.5% Chloramine–T solution (Merck, Germany) for 1 week, followed by storage in distilled water at 25°C. Then each tooth was measured using a digital calliper. Three measurements were taken at the widest points in the bucco-lingual, mesio-distal and occluso-cervical dimensions of the samples, and the averages were calculated. Overall, the tooth dimensions showed a variation within 10%.

In this study, the G*Power V.3.1.9.6 software was utilised to calculate a 95% confidence level (1-α) and 80% test power (1-β). At least 135 teeth were required to obtain an effect size of $f=0.30$ between the study groups, and $n=15$ teeth were used in each group. Potential cracks and fractures in the teeth were examined using a stereomicroscope (Stemi 2000 C, Zeiss, Oberkochen, Germany) at 25× magnification, and any teeth with detected cracks were excluded. The teeth were embedded in self-curing acrylic resin (Imicryl, Konya, Turkey) within PVC cylinders (3 cm in height and 2 cm in diameter), with the resin set 1 mm apical to the cementoenamel junction (CEJ). Subsequently, all samples were randomised using blinding and assigned to control and test groups.

2.1 | MOD Cavity Preparation and Endodontic Treatment

The teeth were endodontically treated and prepared, except for fifteen teeth in the control group. MOD cavities were prepared with a 4° tapered diamond bur with rounded edge (ISO # 806 314 544514 021, Komet, Germany), ensuring 3-mm thick buccal and lingual cavity walls with the help of a digital calliper. Both mesial and distal aspects of the gingival walls were prepared to a depth of 1 mm coronal to the CEJ. Following every five preparations, a new bur was used. The root canals were shaped using ProTaper rotary instruments (Dentsply/Sirona, Ballaigues, Switzerland) up to size # 25 (F2) in mesial root canals and up to #30 (F3) in distal root canals at the working lengths. A total of 2 mL of 2.5% NaOCl was utilised between instrument changes. All irrigation procedures were conducted using a size-27 gauge blunt-tip needle (Ultradent, South Jordan, UT, USA). During the irrigation process, the needle was positioned 1 mm from the working length and moved back and forth. Following instrumentation, each canal was rinsed with 5 mL of 17% EDTA and 5 mL of 2.5% NaOCl, and then dried using paper points. Single gutta-percha cones (Dentsply/Sirona, Ballaigues, Switzerland) were lightly coated with sealer (AH Plus; Dentsply/Sirona, Konstanz, Germany) and inserted into the root canals. After obturation, excess gutta-percha was removed with a heated plugger, and no further vertical condensation was performed. The residual sealer in the pulp chamber was removed by blotting with a cotton pellet impregnated with 70% ethyl alcohol. To avoid a detrimental effect on adhesion, minimal preparation was performed by three passes at slow speed (5000 rpm) with a diamond rond bur (ZR6801.FG.018, Komet, Germany) on the dentin surface.

2.2 | The Groups

2.2.1 | Positive Control Group ($n=15$): Intact Teeth (No Preparation)

One hundred thirty-five endodontically treated specimens were randomly divided into three groups ($n=45$) according to the preparation techniques (Figure 2):

2.2.2 | Group 1 (MOD Preparation)

Preparation of MOD cavity with 3 mm thick buccal and lingual axial walls, mesial and distal gingival margins 1 mm coronal to CEJ.

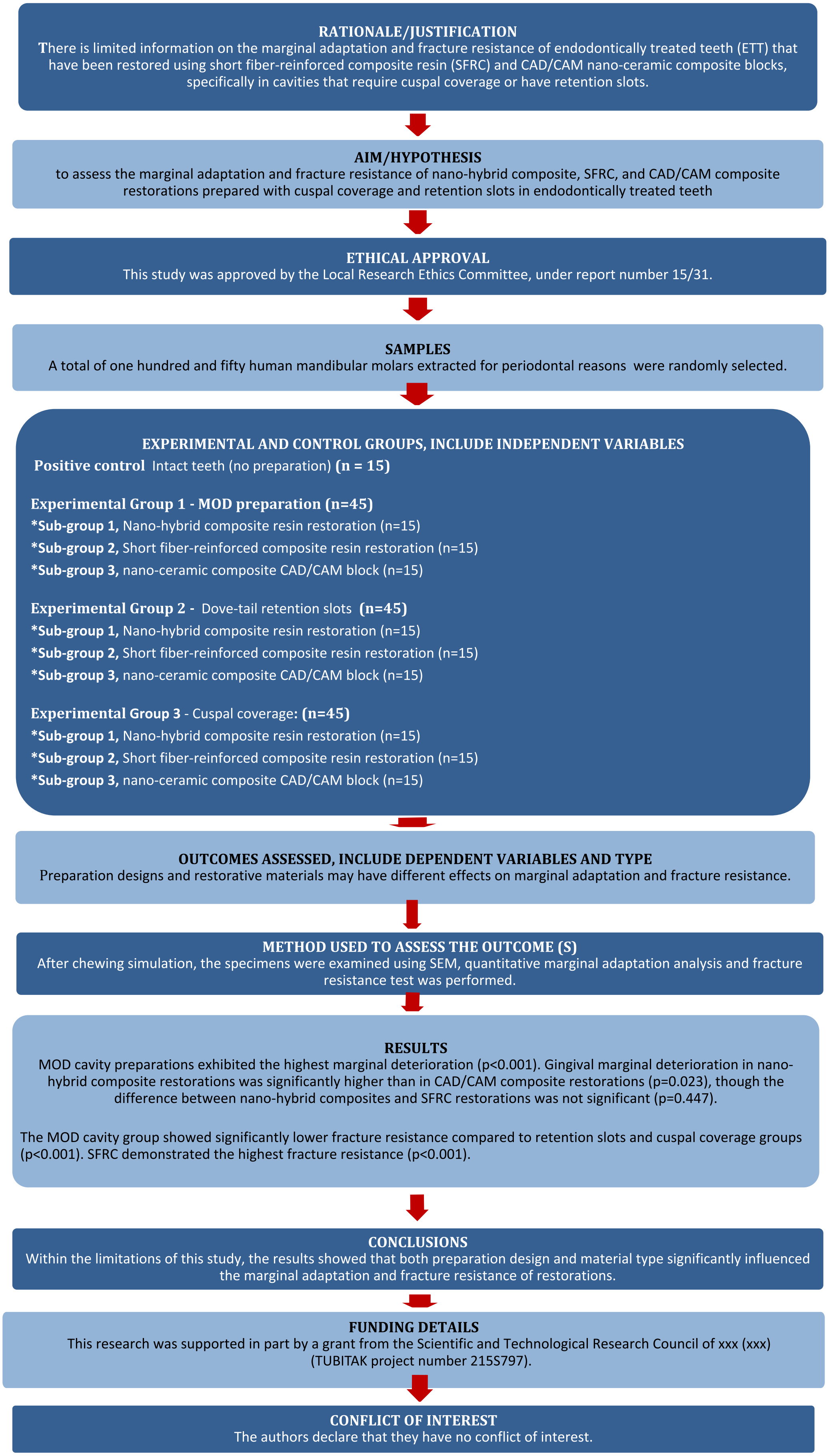

FIGURE 1 | PRILE 2021 flow chart.

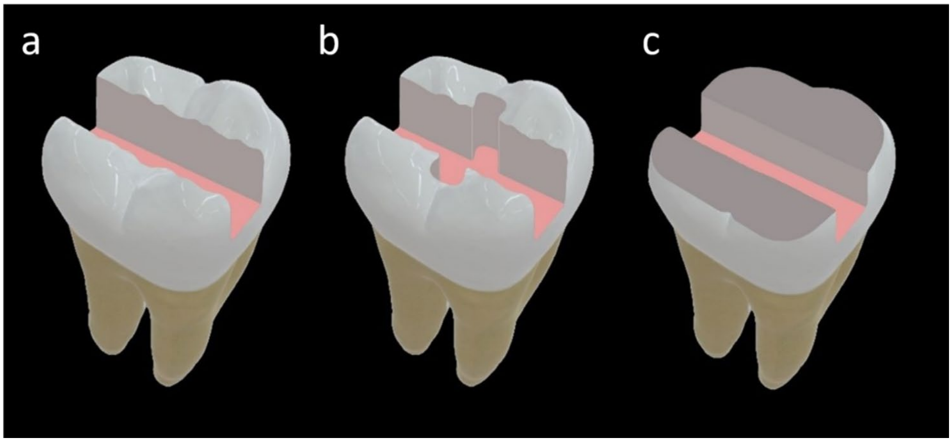

FIGURE 2 | Preparation designs (a) MOD, (b) retention slot and (c) cuspal coverage.

2.2.3 | Group 2 (Dove-Tail Retention Slots)

MOD cavity with a pair of dovetail retention slots of 1.5 × 1.5 mm. The slots were prepared with a diamond bur (ISO # 806 314 544514 016, Komet, Germany), in the midpoint of the lingual and buccal axial walls, at two-thirds of the height of the cavity wall. Buccal and lingual axial walls of a thickness of 3 mm were prepared on the occlusal surface.

2.2.4 | Group 3 (Cuspal Coverage)

MOD cavity with 2-mm reduced cusps using 2-mm depth bur (845KRD.314.025) and long parallel chamfer diamond bur (ISO # 806 314 290514 018, Komet, Germany). The remaining occluso-gingival height of the cavities was measured from the CEJ with a mean of 4.6 mm. The mean mesio-distal length of the cavities was measured as 10.2 mm. 3 mm thick buccal and lingual axial walls, mesial and distal gingival margins 1-mm coronal to CEJ.

Each preparation group was further divided into three sub-groups by the restorative material types to be used (Table 1).

2.2.4.1 | Sub-Group 1, Nano-Hybrid Composite Resin Restoration (n = 15). Following the placement of the anatomically contoured metal matrix band (Super Mat Matrix System KERR HAWE), the enamel was etched with 35% orthophosphoric acid (Scotchbond Etchant, 3M, St. Paul, MN, USA) selectively, rinsed for 30 s and dried. A universal adhesive system (Scotchbond Universal, 3M, St. Paul, MN, USA) was applied according to the manufacturer's recommendations. Nano-hybrid composite resin (Filtek Z550, 3M, St. Paul, MN, USA) was applied with a centripetal incremental placement technique. Following the placement of a 1-mm layer thickness of composite resin to the mesial and distal proximal walls, the restoration was built up with 2 mm composite layers obliquely. Each layer was light-cured for 20 s using an LED light-curing unit (Valo Cordless, Ultradent, USA). After removing any excess composite material, the restoration was finished with an extra-fine diamond bur (ISO # 806 314 277504 018, Komet, Germany), and polished with a silicone tip (Enhance, Dentsply/Sirona, Konstanz, Germany) (Figure 3).

2.2.4.2 | Sub-Group 2, Short Fibre-Reinforced Composite Resin Restoration (n = 15). The interproximal walls were created first to both reduce polymerisation shrinkage and ensure that the SFRC was not exposed. After building of the mesial and distal proximal wall with the composite used for sub-group 1, Fibre-reinforced composite (everX Posterior, GC Corporation, Tokyo, Japan) with ~4 mm thickness was inserted into the cavity up to 2 mm to occlusal space. The last 2-mm thickness increment, as an overlaying layer, was placed using nano-hybrid composite resin. Each composite increment was cured for 20 s using an LED light-curing unit (Valo Cordless, Ultradent, USA).

2.2.4.3 | Sub-Group 3, Nano-Ceramic Composite CAD/CAM Blocks (n = 15). After scanning preparations with Cerec Omnicam (Dentsply/Sirona, Bensheim, Germany), the restoration was designed using software and produced from composite CAD/CAM blocks (Lava Ultimate, 3M, St. Paul, MN, USA). After finishing and polishing the restoration, the inner surface was treated with tribo-chemical coating (CoJet, 3M, Seefeld, Germany). Following the application of silane (Ultradent, South Jordan, UT, USA), the dual-cure resin cement (Rely-X Ultimate, 3M, St. Paul, MN, USA) was applied and cured for 20 s in all aspects (Figure 4). All specimens were stored in distilled water at 37°C.

2.3 | Thermomechanical Aging Process

All specimens were subjected to a chewing simulator (Analitik Medikal, Gaziantep, Turkey) to imitate 2 years of thermomechanical fatigue (Figure 5). The two-year chewing simulation was carried out with a total of 480 000 load cycles under 49 N force at a frequency of 1.7 Hz [13]. The movement involved 3 mm vertical and 1.5 mm horizontal glides on the centre of the occlusal surface and thermal cycling for 2000 times (5°C–55°C).

2.4 | Marginal Adaptation Analysis

To quantitatively analyse marginal adaptation, all specimens were examined using a scanning electron microscope (SEM LS-10, Zeiss, Germany) at 80× magnification, both before and after the aging process. The occlusal and gingival margins, as well as the mesial and distal proximal margins of each tooth, were

TABLE 1 | Materials used in the present study.

Material		Composition*	Manufacturer	Batch no.
Scotchbond Etchant Gel	Etching agent	Phosphoric acid, synthetic amorphous silica, water	3 M, St. Paul, MN, USA	N414370
Scotchbond Universal Adhesive	Universal bonding agent	MDP, dimethacrylate, vitrebond copolymer, filler, ethanol, photo-initiator, water, silane	3 M, St. Paul, MN, USA	D82229
Filtek Z550	Nano-hybrid composite	UDMA, Bis-GMA, Bis-EMA(6) silane treated ceramic, silane treated silica	3 M, St. Paul, MN, USA	N334740
everXPosterior	Fibre-reinforced composite	Bis-GMA, TEGDMA, glass fibre, barium glass, silicon dioxide, PMMA (polymethylmethacrylate), photoinitiators	GC Corp., Tokyo, Japan	1 307 052
Lava Ultimate CAD/CAM	Nano-ceramic resin composite	Silica nanomers, zirconia nanomers, silica-zirconiananoclusters, Bis-GMA, Bis-EMA, UDMA, TEGDMA	3 M, St. Paul, MN, USA	N368842

Note: Bis-EMA(6), bisphenol A polyethylene glycol dietherdimethacrylate; Bis-GMA, bisphenol A diglycidyl methacrylate; HEMA, 2-hydroxyethyl methacrylate; MDP, 10-methacryloyloxydecyl dihydrogenphosphate; TEGDMA, triethyleneglycoldimethacrylate; UDMA, urethanedimethacrylate.
*Manufacturers' data.

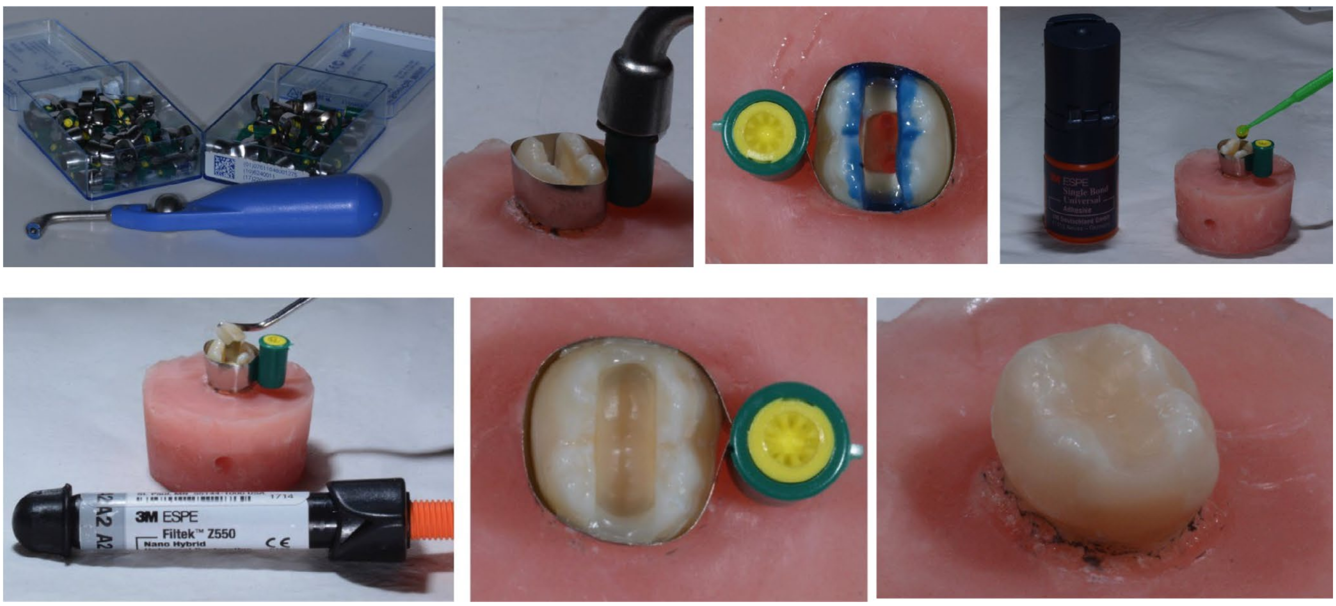

FIGURE 3 | Recordings from the restorative procedures of direct composite group with MOD preparation.

evaluated separately. Marginal micromorphology was assessed and classified as either a 'continuous margin' or a 'marginal gap' which was then expressed as a percentage relative to the total margin length (Figure 6).

2.5 | Fracture Resistance Test

Fracture resistance was measured using a universal testing machine (AGS-X, Shimadzu, Tokyo, Japan). A 6-mm diameter steel spherical tip was located at the center of the occlusal surface, with force applied at a speed of 0.5 mm/min perpendicular to the long axis of the tooth until fracture occurred (refer to Figure 7a,b). The fracture force was recorded in Newtons (N).

2.6 | Fracture Types Were Categorised as Follows

1. Restorable failures: Fracture lines located at or up to 1 mm apical to the cementoenamel junction (CEJ).
2. Non-restorable failures: The fracture lines are more than 1 mm apical to the CEJ, including vertical root fractures (Figure 7c).

2.7 | Statistical Analysis

All data were analysed using statistical software (SPSS Statistics v.20.0, IBM Corp., Armonk, NY, USA) with a significance level set at 0.05. Marginal adaptation data for the

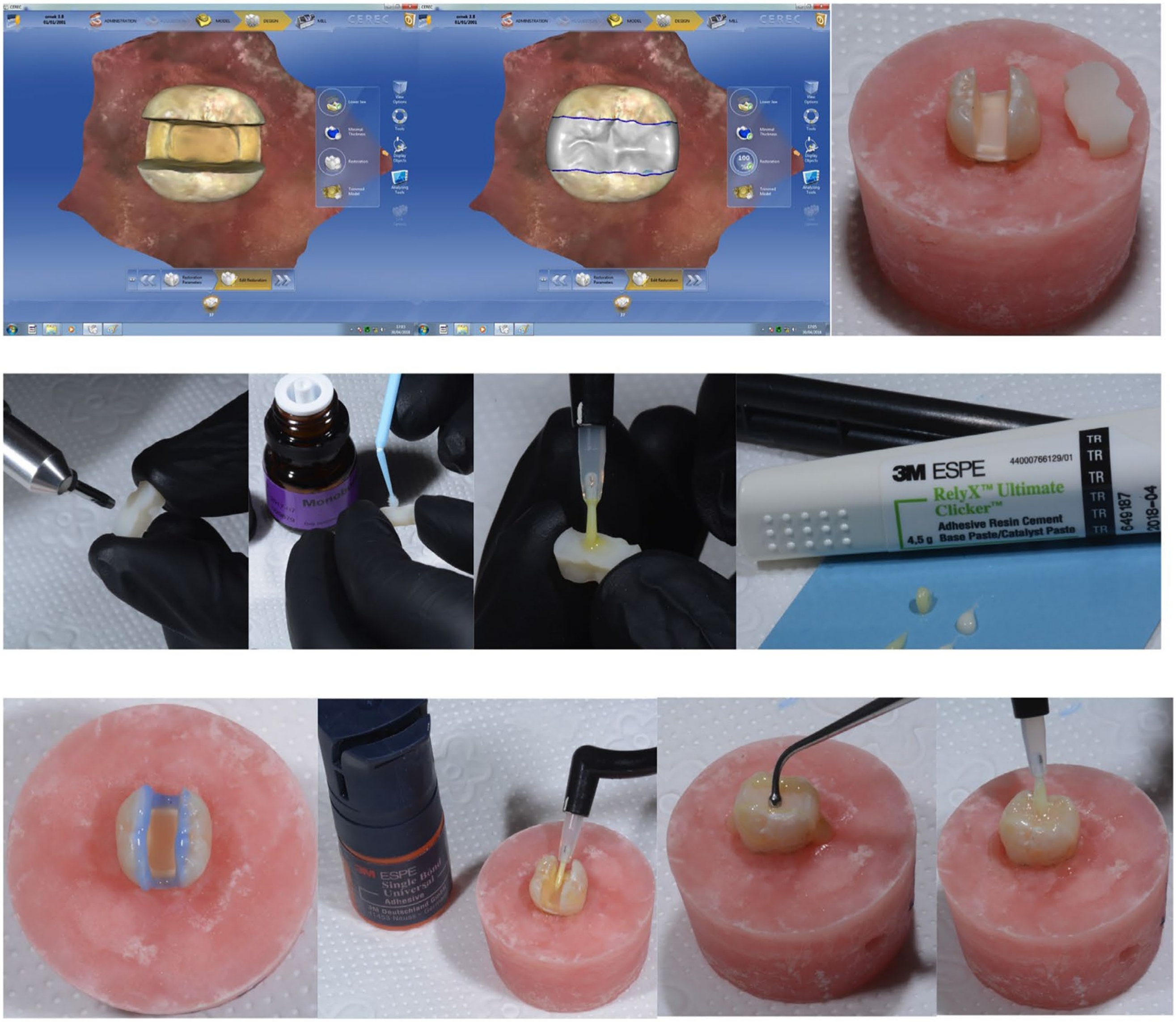

FIGURE 4 | Recordings from the restorative procedures of CAD/CAM nano-ceramic composite group.

gingival and occlusal margins, obtained from the marginal deterioration analysis, were analysed using a multiple analysis of variance (ANOVA) based on preparation and material type. The fracture strength data were evaluated with two-way ANOVA, and group comparisons were made using Tukey's post hoc test. Fracture types were further analysed using the chi-square test.

3 | Results

3.1 | Marginal Adaptation

The merged images obtained from scanning the occlusal, mesial and distal gingival walls of the teeth are shown in Figure 8. The mean and standard deviations of marginal deterioration at the gingival and occlusal margins of the restorations are presented in Tables 2 and 3.

Covariance analysis revealed no significant effect of initial marginal deterioration on the groups ($p > 0.05$). However, multi-way analysis of variance showed a significant effect of the preparation type on the marginal adaptation of both the occlusal and gingival margins ($p < 0.05$). While the material type did not have a significant effect on the occlusal margins, it did significantly impact the marginal adaptation of the gingival margins ($p < 0.05$).

In terms of preparation type, marginal deterioration at the gingival margins was significantly higher in MOD (mesio-occluso-distal) preparations compared to the other preparation groups ($p < 0.001$). However, the difference between retention slot preparations and cuspal coverage preparations was not statistically significant ($p = 0.67$). Gingival marginal deterioration in nano-hybrid composite restorations was significantly higher than in CAD/CAM composite restorations ($p = 0.023$), though the difference between nano-hybrid composites and SFRC restorations was not significant ($p = 0.447$).

FIGURE 5 | Changes in specimens after thermomechanical ageing.

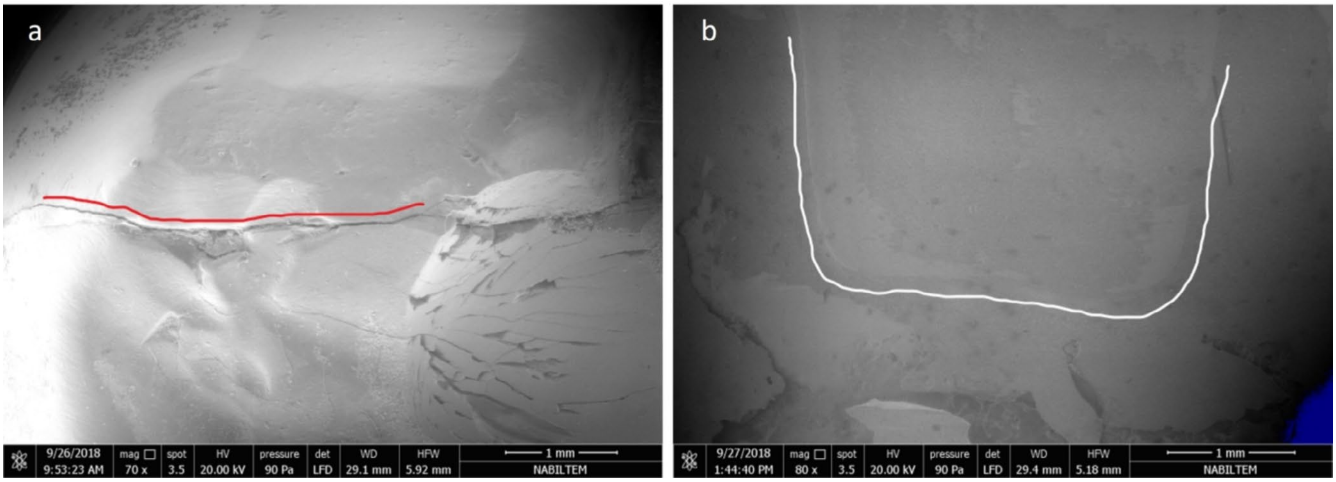

FIGURE 6 | SEM image of deterioration at the margin (a) and integrity at the margin (b).

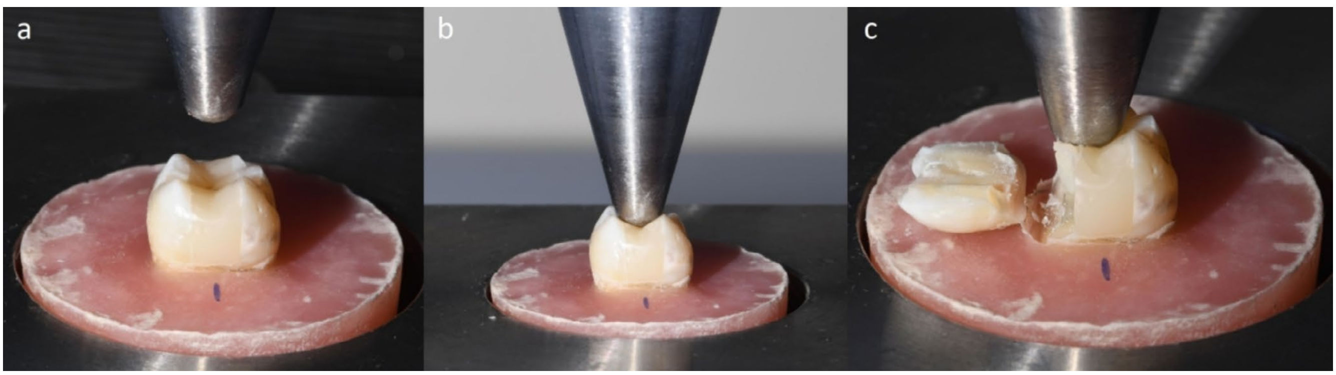

FIGURE 7 | Recordings from fracture test: (a) placing the specimen into the universal testing machine (b) delivering the load with spherical tip (c) non-restorable failure.

Regarding occlusal margins, marginal deterioration in samples with MOD preparations was significantly higher than in other preparation groups ($p < 0.001$). The difference between retention slot and cuspal coverage preparations was not statistically significant ($p = 0.919$). Additionally, no significant differences were observed among restorations made with nano-hybrid composite, short fibre-reinforced composite, or CAD/CAM nano-ceramic composite blocks for occlusal margins ($p > 0.05$).

3.2 | Fracture Resistance

After 2 years of thermal cycle chewing simulation applied to the samples, only one sample restored with nano-hybrid composite resin by MOD cavity preparation did not survive the simulation and was rated as pre-test failure. The mean fracture resistance values (N) and standard deviations are shown in Table 4. A two-way ANOVA revealed that fracture resistance was significantly influenced by both the type of cavity preparation and

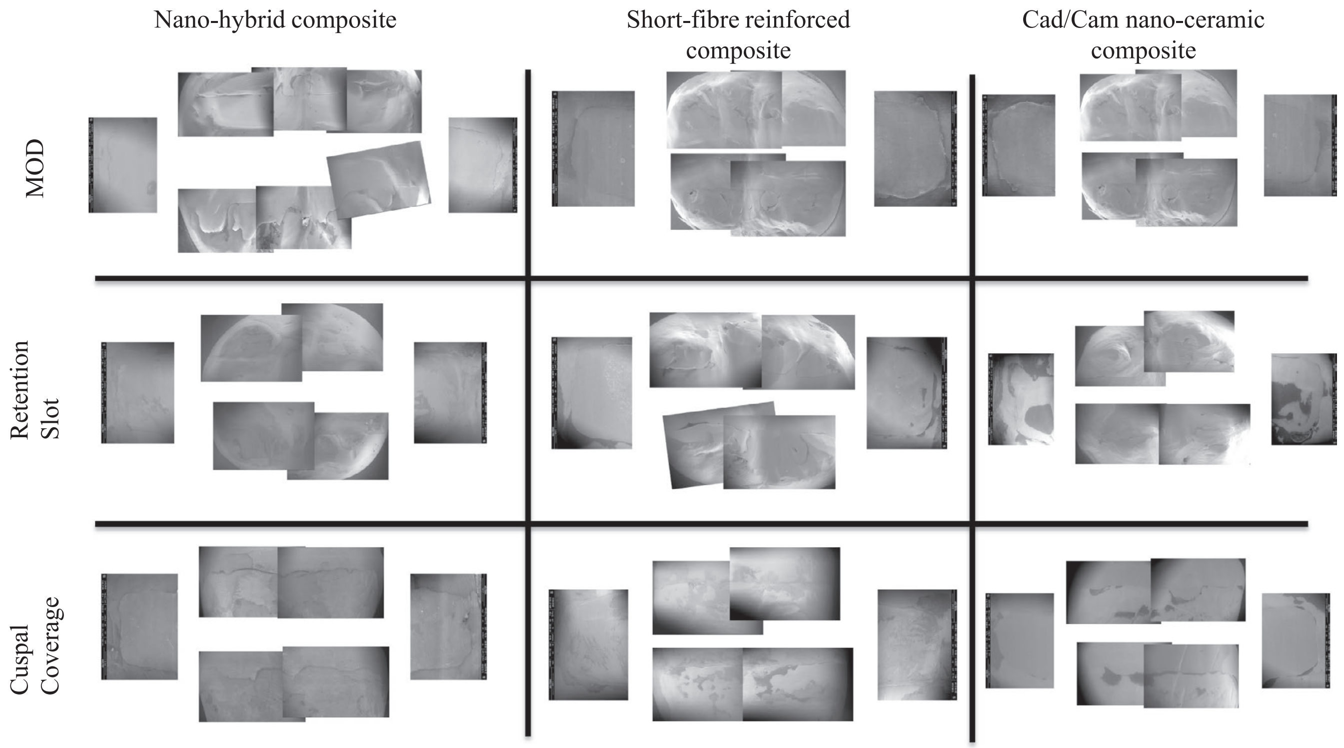

FIGURE 8 | Merged SEM images of the tested restorations.

TABLE 2 | Means and standard deviations of the marginal deterioration (%) at the gingival margins.

	Nano-hybrid composite	Short-fibre reinforced composite	Cad/Cam nano-ceramic composite
MOD	16.73 (9.22)^{A,a}	15.38 (7.71)^{A,a}	8.61 (5.92)^{B,a}
Retention slot	5.03 (3.85)^{A,b}	4.24 (3.08)^{A,b}	4.17 (5.82)^{A,a}
Cuspal coverage	8.89 (6.6)^{A,a,b}	6.20 (5.49)^{A,b}	7.27 (6.53)^{A,a}

Note: Different capital letters on the same line indicate statistical significance between groups. Different lowercase letters in the same column indicate statistical significance between groups.

TABLE 3 | Means and standard deviations of the marginal deterioration (%) at the occlusal margins.

	Nano-hybrid composite	Short-fibre reinforced composite	Cad/Cam nano-ceramic composite
MOD	18.98 (5.97)^{A,B,a}	24.37 (10.85)^{A,a}	10.96 (6.29)^{B,a}
Retention slot	11.45 (7.59)^{A,a,b}	5.56 (3.05)^{A,b}	12.66 (7.12)^{A,a}
Cuspal coverage	7.02 (2.64)^{A,b}	10.66 (4.63)^{A,b}	10.44 (3.99)^{A,a}

Note: Different capital letters on the same line indicate statistical significance between groups. Different lowercase letters in the same column indicate statistical significance between groups.

the restorative material used ($p < 0.05$). However, no significant interaction was found between the preparation design and the type of restorative material ($p = 0.88$).

The control group with intact teeth exhibited the highest fracture resistance values among all the test groups ($p < 0.05$). Samples with MOD preparations had significantly lower fracture resistance compared to the other preparation groups ($p < 0.001$). No significant difference was observed between samples with retentive groove and cusp coverage preparations ($p > 0.05$). Among the restorative materials, samples restored with short fibre-reinforced composite resin demonstrated significantly higher fracture resistance than the other groups ($p < 0.05$). However, there was no significant difference between samples restored with nano-hybrid composite resin and CAD-CAM nano-ceramic composite blocks ($p > 0.05$).

The majority of fractures in this study were categorised as non-restorable, as shown in Figure 9. The chi-square test indicated no significant differences in fracture patterns among the restorative material groups ($p > 0.05$), although a significant difference was observed among the preparation groups ($p < 0.05$). Non-restorable fractures occurred significantly more frequently in the cuspal coverage group ($p < 0.05$).

TABLE 4 | Mean fracture resistance (N) values and standard deviations of each preparation design and restorative material combination.

	Nano-hybrid composite	Short-fibre reinforced composite	Cad/Cam nano-ceramic composite
MOD	964.5 (327.5)^{A,a}	1275.8 (196.5)^{A,a}	1002.2 (371.4)^{A,a}
Retention slot	1425.3 (392.3)^{A,a}	2013.6 (410.4)^{B,b}	1485.6 (510.7)^{A,b}
Cuspal coverage	1473.7 (244.2)^{A,a}	2415.1 (363.4)^{B,b}	1781.4 (256.7)^{A,b}
Positive control		2968.3 (872.9)^{c}	

Note: Different capital letters on the same line indicate statistical significance between groups. Different lowercase letters in the same column indicate statistical significance between groups.

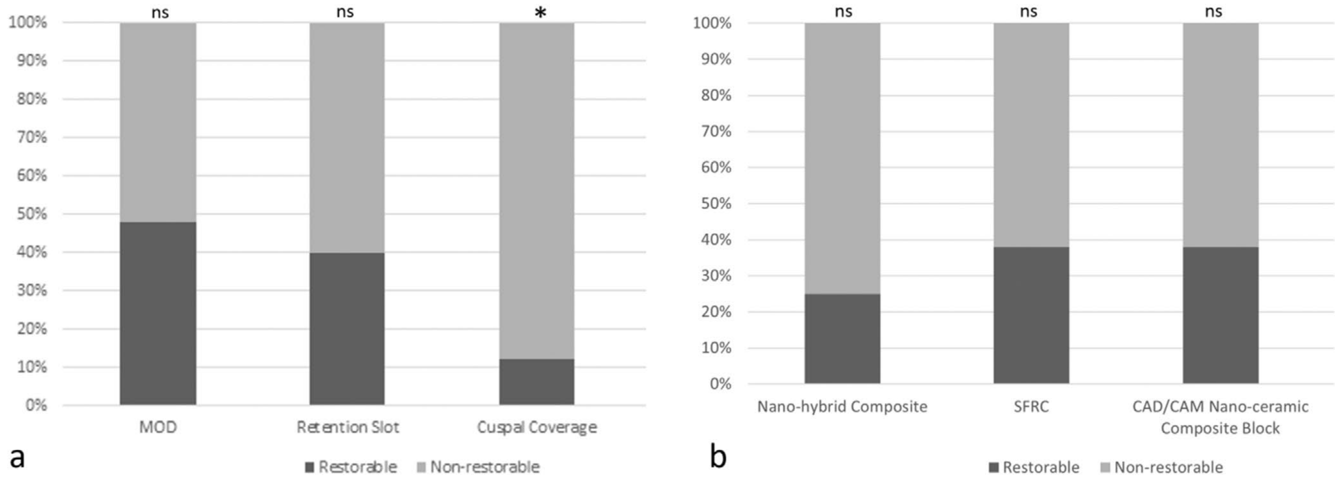

FIGURE 9 | Distribution of fractures (a) according to preparation design (b) according to restorative material. *significance ($p < 0.05$). ns, non significance ($p > 0.05$).

4 | Discussion

The results of the current study indicate that the first null hypothesis should be rejected, as there were significant differences in marginal adaptation and fracture resistance among the various preparation designs. Similarly, the second null hypothesis was rejected, as a statistically significant difference was observed in the marginal adaptation and fracture resistance of teeth restored with different materials.

In clinical settings, dental restorations face both biochemical challenges and mechanical loads, which contribute to the accelerated deterioration of the bond between the tooth and the restoration. To replicate these clinical conditions, restorations in this study were subjected to thermo-mechanical loading prior to testing for marginal adaptation and fracture resistance.

Based on the marginal adaptation analysis in this experiment, cavity design was found to be a significant factor influencing the quality of gingival and occlusal margins after aging. Marginal deterioration at both the gingival and occlusal levels was significantly greater in MOD preparations compared to other preparation groups. This difference in marginal adaptation could be attributed to the fact that MOD cavities lack an auxiliary preparation technique to withstand thermal and occlusal stresses, whereas cuspal coverage positively affects the cavity configuration factor and reduces tubercle flexibility. Recent studies reported that the quality of margins in overlay restorations improved due to a reduction in the cavity configuration factor (C-factor) resulting from the shortening of cusps [14, 15]. Additionally, retention slots may provide mechanical locking and help resist polymerisation shrinkage stresses [16]. A significant difference in gingival marginal adaptation was observed among the various restorative material groups. Numerous studies in the literature have highlighted that FRC resin materials possess shrinkage stress absorption properties, which lead to reduced tubercle deflections, improved marginal adaptation and lower microleakage compared to conventional composite resins [17, 18]. However, some studies have reported that SFRC resin materials either do not significantly affect the microleakage and marginal adaptation of restorations or result in less marginal adaptation [19, 20].

These investigations also include evaluations of the marginal adaptation of restorations with FRC materials supported by cuspal coverage. In a recently published study, intracoronal FRC restorations in molar teeth exhibited more gap-free margins in enamel compared to resin composites when evaluated in terms of marginal quality [21]. In our study, there was no significant difference in gingival marginal deterioration between the samples restored with nano-hybrid composite and SFRC.

Studies of CAD/CAM composite materials reported increased fatigue resistance compared to direct composites [22], and their reduced polymerisation shrinkage makes them more resistant to marginal deterioration and microleakage [23]. In this study, for the MOD preparation design, gingival marginal deterioration of CAD/CAM nano-ceramic composite restorations was found to be significantly lower than deterioration in nano-hybrid composite and SFRC resin restorations.

It has been suggested that the most important determinant of the durability of endodontically treated molars is the remaining tooth structure, as the loss of the marginal ridge has been shown to reduce cuspal stiffness [24]. Therefore, in this experiment, MOD cavities with 3 mm thick gingival walls, located 1 mm coronal to the CEJ both mesially and distally, were prepared to evaluate fracture resistance and determine the strengthening effects of different cavity designs and restorative materials. This study demonstrated that teeth prepared with MOD cavities had significantly lower fracture resistance values compared to those with retention slots or cuspal coverage designs.

For restoring MOD cavities with SFRC and indirect restorations, incorporating cusp coverage and retention slot preparation could be beneficial in increasing fracture resistance [25, 26]. It is reasonable to expect an increase in fracture resistance when special preparations are made and more durable materials, such as porcelain, hybrid and composite blocks, or short fibre-reinforced composite resins, are used. In fact, direct composite restorations using various preparation methods can enhance the fracture resistance of teeth [26, 27], though no statistically significant difference was found in this study. Conversely, some reports suggest that the cuspal coverage technique does not affect the fracture resistance of ETT [28, 29]. Similar to our findings, these studies observed no significant difference in fracture resistance between direct composite resin restorations with or without cuspal coverage.

In the literature, only one study was found that examined the effect of the retention slots on fracture resistance. The authors concluded that the dovetail-shaped retention slots positively impact fracture resistance [30]. They determined that retention slots did not weaken the tooth's resistance and, in fact, increased the fracture resistance of the restoration by creating mechanical locking between the restoration and tooth tissue. In line with their findings, our study showed that the retention slot preparation technique, combined with more durable materials such as SFRC resin, improved the fracture resistance of ETT.

In studies showing the effectiveness of SFRC in ETT with MOD cavities, it was concluded that it was more successful than flowable bulk-fill composite in direct restorations [31], and that it increased loading performance in direct or indirect overlay restorations [32]. Several experiments have treated posterior teeth with significant substance loss using overlay restorations with SFRC as the core material and direct composite resin on the surface. Research in this area has concluded that these restorations did not improve fracture resistance or result in the formation of any repairable fractures [33, 34].

Recent studies have investigated the effect of cuspal coverage on the fracture resistance of SFRC material. One study reported that SFRC restorations exhibited a higher load-bearing capacity compared to other direct onlay restorations made with bulk-fill or conventional composite materials [35]. In another study, the group with the highest fracture resistance was the one where SFRC was used in combination with conventional composite materials [36]. In one study, fibre-reinforced composite resin demonstrated higher fracture resistance than the CAD-CAM composite groups with which it was compared [37]. Our findings align with these results, as the SFRC group with cuspal coverage demonstrated the highest fracture resistance among all groups.

In this study, the majority of specimens exhibited 'non-restorable' fracture formation. We found significant differences in fracture patterns among the preparation groups, but not among the restorative material groups. Teeth with cuspal coverage exhibited a significantly higher percentage of non-restorable fractures compared to other preparation designs. This can be explained by the fact that both adhesive and cohesive fractures occur as a result of restorations being exposed to high forces during fracture, which may increase the likelihood of root fractures. However, it is important to remember that the force applied in fracture tests is higher than what is typically encountered in clinical conditions. In the mouth, materials usually fail not from sudden high forces but from accumulated fatigue over time.

This study has several limitations that should be acknowledged to contextualise the findings. First, the use of extracted human mandibular molars may not fully represent the in vivo conditions of oral environments where biological factors such as saliva, bacteria and individual variations in occlusal forces play critical roles in restoration durability. Although thermo-mechanical loading was applied to simulate clinical conditions, it cannot entirely replicate the cumulative fatigue and biochemical degradation that restorations experience in a natural setting. Also, we acknowledge the limitation that mounting the specimens in acrylic resin does not fully replicate the biomechanical properties of the periodontal ligament and alveolar bone, which may influence the fracture pattern. However, this method is widely used in in vitro studies to standardise specimen positioning and ensure reproducibility of the results. Future studies could incorporate alternative mounting techniques, such as artificial PDL simulation, to better mimic clinical conditions.

Another limitation concerns the range of materials tested, including short fibre-reinforced composite (SFRC) and CAD/CAM nano-ceramic composite restorations. While these materials were selected based on their clinical relevance, the findings may not be generalisable to all types of composite materials or other restoratives, such as ceramics or resin-modified glass ionomers, that may exhibit different behaviour in terms of polymerisation shrinkage, bond strength and marginal adaptation. Moreover, differences in operator technique, especially with direct composite applications, could influence outcomes in real-world clinical settings.

Lastly, the study's sample size and methodology limit the ability to analyse other potentially impactful factors, such as the influence of different preparation angles or cavity depth variations on marginal adaptation and fracture resistance. Future research with larger sample sizes and a broader range of preparation configurations could offer deeper insights and enhance the generalisability of these findings across diverse clinical cases.

5 | Conclusion

Within the limitations of this study, the results showed that both preparation design and material type significantly influenced the marginal adaptation and fracture resistance of restorations. Significantly less deterioration was observed in both the gingival and occlusal margins for cuspal coverage and retention slot preparations compared to MOD preparations. While the restorative material did not affect occlusal margin deterioration, nanohybrid resin exhibited the highest deterioration at the gingival margin. The results suggest that for ETT with MOD cavities, cuspal coverage preparation, particularly when combined with short fibre-reinforced composite (SFRC), provides superior fracture resistance and marginal adaptation. Therefore, clinicians are advised to prefer cuspal coverage designs over MOD-only preparations to enhance the longevity of restorations. When cuspal coverage is not feasible, retention slots may be considered as an alternative to improve mechanical stability.

Author Contributions

H.K.B. contributed to investigation, methodology and writing (original draft). M.Ş. contributed to visualisation, reviewing and editing. E.G.U.U. contributed to investigation and data acquisition. H.H. contributed to investigation, methodology and supervision. B.Y. contributed to conceptualisation, methodology and statistical analysis.

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Ethics Statement

This study was approved by the Research Ethics Committee of Katip Çelebi University, under report number 15/31.

Consent

All participants were freely invited, and those who accepted signed an informed consent approved and stamped by the local ethics committee.

Conflicts of Interest

The authors declare no conflicts of interest.

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