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Evaluation of Surface Treatment Methods on Fatigue Resistance and Static Flexural Bond Strength in CAD-CAM Resin Composites

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Abstract: ***This in vitro study aimed to assess the influence of different surface treatments prior to repairing a CAD-CAM resin composite on both fatigue and static flexural bond strength when bonded to a direct resin composite. CAD-CAM resin composite blocks (Tetric CAD) were ground and divided into three treatment groups: (1) aluminum oxide air-abrasion (50-µm particle size) followed by adhesive application (AA + AD group), (2) adhesive application only (AD group), and (3) silane treatment (SIL group). For comparison, both direct (DIR-RC) and indirect resin composites (IND-RC) were tested to determine their cohesive strength. The composite blocks were sectioned into beams (1 × 2 × 12 mm) and subjected to flexural bond strength tests under static loading (n = 10; 1 mm/min) and cyclic fatigue loading (n = 15; initial load = 5 N, frequency = 1.4 Hz, step increment = 5 N, 10,000 cycles per step) using a ball-in-hole testing setup. Finite element analysis was used to analyze the results in megapascals (MPa). Additionally, failure modes and surface topography were evaluated.***

Under static loading, both the AA + AD and AD groups demonstrated significantly higher bond strength compared to the SIL group. However, after fatigue loading, no statistically significant differences were observed among the surface treatment groups. The IND-RC group exhibited the highest flexural strength under both static and fatigue conditions. Fatigue loading reduced bond strength in all experimental groups, with the SIL group showing the greatest reduction.

Importantly, none of the surface treatments fully restored the original strength of the CAD-CAM resin composite. However, surface grinding, with or without air abrasion, followed by adhesive application, provided comparable and favorable results. Thus, adhesive application in combination with surface grinding appears to be an effective strategy for the clinical repair of CAD-CAM resin composites.

Keywords: CAD/CAM composite Fatigue, Finite element analysis, Intraoral repair, Resin composite

I. INTRODUCTION

Technological advancements have enabled the fabrication of indirect restorations with fewer inherent defects, improved efficiency, and enhanced clinical outcomes . Notably, the Computer-Aided Design–Computer-Aided Manufacturing (CAD-CAM) system allows for the production of restorations within a single clinical appointment . Among the various prefabricated machinable blocks available, ceramic and resin-based materials are widely utilized though CAD-CAM ceramics offer excellent aesthetics and have demonstrated long-term clinical success rates of up to 95% after 3 years and even after 5 years , their brittle nature makes them prone to fractures . In contrast, CAD-CAM resin-based materials have gained popularity due to their elastic modulus being closer to that of dentin, promoting better stress distribution across the restorative complex. These materials also offer practical advantages, such as ease of milling and fewer post-processing steps compared to ceramics. Additionally, CAD-CAM resin composites address some of the limitations associated with direct resin composites, including polymerization shrinkage, interlayer defects, and inferior mechanical properties. The reported clinical success rates for indirect resin-based restorations range from 97.5% after 5 years to 83% after 11 years . While long-term clinical data on CAD-CAM resin composite restorations are still lacking, short-term studies have reported success rates of 85.7%, 90%, and even 100% after 2 years. Despite these promising outcomes, CAD-CAM resin composites remain vulnerable to fatigue failure when exposed to mechanical stress and corrosive environments, which often results in chipping or fractures, especially in the occlusal region. In such cases, a common and conservative clinical solution is to perform a direct repair using resin composite materials. This approach is feasible due to the inherent reparability of the CAD-CAM resin composite. Direct repair offers a cost-effective, time-saving alternative to full restoration replacement, while also extending the clinical lifespan of the original restoration. Although CAD-CAM resin composites and direct resin composites share similar chemical compositions, differences in factors such as the degree of polymer conversion can compromise their bond strength.

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Since CAD-CAM materials are polymerized under industrial conditions, achieving a strong bond requires effective surface treatment to create reactive free radicals and facilitate adhesion. A recent systematic review and meta-analysis emphasized that any form of surface pretreatment—such as aluminum oxide air-abrasion, silica-coated abrasion, hydrofluoric acid etching, or diamond bur grinding—outperforms the absence of treatment, particularly in CAD-CAM materials like Lava Ultimate. The surface treatment process significantly affects the bond strength between resin-based materials and is a critical factor in ensuring a successful repair. Ultimately, because the durability of a restoration is heavily influenced by the strength of its adhesive interface, optimizing this step is essential for long-term clinical success.

II. MATERIALS AND METHODS

A. Study Design

Resin composite (RC) blocks fabricated using CAD-CAM technology (Tetric CAD HT A2, size C14, LOT Z03P53; Ivoclar AG) were modified with a simulated ground surface and randomly allocated into three experimental surface treatment groups prior to repair with a direct resin composite (EvoCeram, Ivoclar AG) (see Fig. 1). The groups were:

AA + AD group: air-abrasion with aluminum oxide followed by adhesive application

AD group: adhesive application only

SIL group: silane application only

Additionally, two control groups comprising unrepaired monolithic specimens—direct resin composite (DIR-RC) and indirect CAD-CAM resin composite (IND-RC)—were included for comparison. Rectangular specimens (1 × 2 × 12 mm) were prepared for mechanical evaluation via static flexural strength and flexural bond strength testing (n = 10), as well as fatigue loading (n = 15), using a ball-in-hole testing device [41,42].

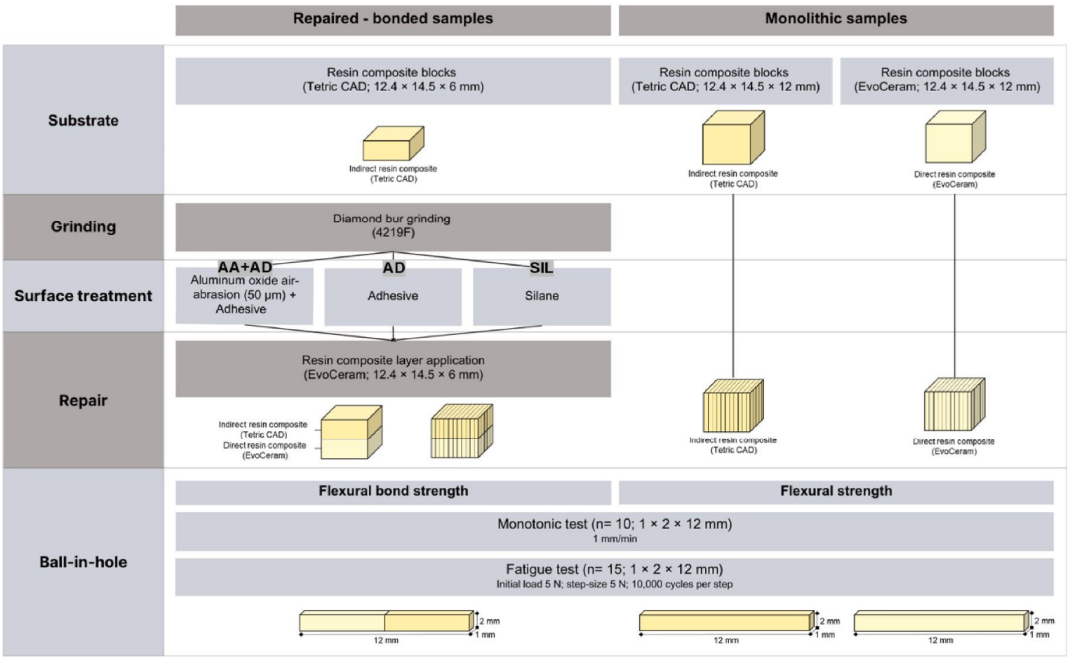


Fig. 1. Flowchart of the study design.

B. Specimen Preparation

For cohesive strength assessment, one CAD-CAM block (Tetric CAD; 12.4 × 14.5 × 18 mm) was cut into a 12.4 × 14.5 × 12 mm block using a precision cutting machine (Isomet, Buehler) equipped with a diamond disc under water cooling (IND-RC group). To fabricate the DIR-RC group, a silicone mold was used to incrementally build up six 2-mm layers of EvoCeram resin composite, with each layer light-cured for 20 seconds (Bluephase N, Ivoclar AG). A final post-curing process was carried out in a curing unit (Dentacolor XS, Heraeus Kulzer) for 240 seconds. Both block types were sectioned into beams (1 × 2 × 12 mm), and their dimensions were verified using a digital caliper (Absolute 500-196-20, Mitutoyo) prior to testing. Half the samples (n = 10) underwent static flexural strength testing after 24 hours of storage, while the remainder (n = 15) were stored in distilled water at 37°C for two weeks before being subjected to fatigue testing.

To prepare the repaired groups, CAD-CAM blocks were sectioned into 12.4 × 14.5 × 6 mm specimens. Surface finishing was standardized by sequential grinding with #400-, #600-, and #1200-grit silicon carbide abrasive papers using a polishing system (EcoMet/AutoMet 250; Buehler) under water cooling. Simulating clinical conditions, surfaces were further roughened using a diamond bur (4219F, KG Sorensen) mounted on a high-speed contra-angle handpiece (T2 REVO R170, Sirona) with water cooling. A permanent marker was applied to ensure complete surface contact with the bur during the grinding process. Bidirectional (x- and y-axis) linear passes were made until all ink was removed. Cleaned surfaces were rinsed with air-water spray for 30 seconds and dried. Surface roughness was quantified via profilometry (SJ-410, Mitutoyo Corporation), measuring Ra and Rz values at six locations (three per axis) to ensure consistency across specimens [44].

C. Direct Repair Procedure

After surface treatment, the specimens were distributed among three groups as indicated in Fig. 1. For the AA + AD group, surfaces were treated using 50 µm aluminum oxide particles for 10 seconds from a 10 mm distance at 1.5 bar pressure. After air-abrasion, specimens were placed in an ultrasonic bath with 70% ethanol for 5 minutes, followed by drying with compressed air for 30 seconds. Adhesive (Adhese Universal; Ivoclar AG) was applied with a microbrush for 20 seconds, gently air-thinned for 10 seconds, and light-cured for 20 seconds (Bluephase N). In the AD group, only the adhesive protocol was applied. For the SIL group, a silane coupling agent (Monobond Plus, Ivoclar AG) was applied to the surface and allowed to react for 60 seconds before air drying for 10 seconds. All groups were repaired with a nanohybrid resin composite (EvoCeram) using a silicone mold to maintain uniform dimensions. Composite was applied in 2-mm increments, each cured for 20 seconds, until reaching a 6 mm height. A glass slide was used during final curing to ensure a level surface. Specimens were then stored in distilled water at 37°C for 24 hours before sectioning into beams (1 × 2 × 12 mm) for mechanical testing. A total of 25 beams per group was generated, with subsets allocated to static and fatigue tests.

D. Mechanical Testing: Flexural Strength and Bond Strength

A ball-in-hole setup was used for both flexural strength and bond strength tests. Specimens were supported on two rollers 10 mm apart, with a 10.1 mm diameter steel ball applying load centrally over the bonding interface [41]. For the static test, loading was performed using a universal testing machine (Instron 6022, USA) at 1 mm/min until failure. Flexural bond strength was calculated using the formula:

$FS = 3PL / 2bh^2$

Where:

P = load at failure (N)

L = support span (10 mm)

b = beam width (mm)

h = beam thickness (mm) [45]

For fatigue testing, parameters were derived from the static results. Testing began at a 5 N load, increasing in 5 N steps, with 10,000 cycles per step. Loads were applied pneumatically until failure (either adhesive interface rupture or beam fracture). Data collected included fatigue failure load (FFL) and number of cycles to failure (CFF) for statistical evaluation [46,47].

E. Finite Element Modeling

Finite element analysis (FEA) was performed to simulate stress distribution during mechanical testing (Fig. 2). Models were developed in Rhinoceros 5.0 SR8 (McNeel North America) to replicate specimen geometry. Simulations were run in ANSYS 19.0 (2018, ANSYS Inc.), incorporating a 10% mesh convergence tolerance. Material properties for Tetric CAD and EvoCeram were defined as isotropic and linearly elastic (Young's modulus: 11.61 GPa and 11 GPa, respectively; Poisson's ratio: 0.3) [48]. Perfect bonding was assumed at the interface. Loads corresponding to both static and fatigue failure were applied to determine peak tensile stress values for each condition [45].

F. Failure and Surface Characterization

After mechanical testing, all specimens were inspected under a stereomicroscope (Discovery V20, Carl Zeiss) at 15× magnification to classify the failure mode. Failures were categorized as:

Adhesive: complete detachment at the bonding interface

Cohesive: failure entirely within the resin composite (either direct or indirect)

Mixed: involving both adhesive and cohesive elements

Representative samples were further examined using scanning electron microscopy (SEM, Evo LS15, Carl Zeiss) at 130× magnification to analyze fracture features. Additionally, SEM at 500× and 10,000× magnifications was employed to assess surface morphology following each preparation step.

III. RESULTS

Prior to the bonding procedures, surface roughness measurements confirmed that all specimens exhibited comparable roughness values following the grinding process. For the Ra (arithmetic average roughness) parameter, the mean ± standard deviation values (in µm) were as follows: AA + AD group: 1.72 ± 0.56, AD group: 1.75 ± 0.32, and SIL group: 1.79 ± 0.21. Similarly, for the Rz (maximum height of the profile) parameter, values were: AA + AD: 10.50 ± 2.76, AD: 10.45 ± 2.43, and SIL: 10.97 ± 2.70.

In the static flexural bond strength test, the IND-RC group demonstrated significantly superior performance, registering the highest strength values ($F = 218.31$, $p < .001$; see Table 1). No statistically significant differences were observed among the DIR-RC, AA + AD, and AD groups. The SIL group showed similar results to the AA + AD group, with no significant distinction between them.

Under fatigue loading conditions, surface treatment groups (AA + AD, AD, and SIL) exhibited no statistically significant differences in flexural bond strength (refer to Fig. 2 and Table 1). Nonetheless, the IND-RC group continued to outperform all others, maintaining the highest fatigue bond strength values ($p < .001$, Fig. 3).

All groups experienced a reduction in flexural strength after fatigue testing. Notably, the SIL group showed the most pronounced strength degradation when compared to the other experimental conditions (Table 1).

Table 1

Mean, standard deviation (SD), and confidence interval (CI 95 %) of flexural bond strength (in MPa) and decrease (in %) (repaired sample) in the static (n = 10) and in fatigue (n = 15) test, and number of cycles for failure (CFF) of the different groups.

Groups	Static		Fatigue		Decrease (%)
	Mean (SD)[a]	CI 95 %	Mean (SD)[b]	CI 95 %	
AA + AD	78.1 (17.8) BC	65.4–90.8	43.8 (10.4) BC	38.1–49.6	56.1
AD	90.6 (11.4)[B]	82.5–98.7	45.4 (6.5) BC	41.8–49.0	50.1
SIL	61.7 (19.7) C	47.6–75.8	36.1 (12.2) C	29.3–42.8	58.4
DIR-RC	90.5 (9.7)[B]	83.6–97.4	48.2 (8.5)[B]	43.4–52.9	53.2
IND-RC	262.5 (25.0)[A]	244.6–280.4	144.7 (22.5)[A]	132.2–157.1	55.1

Regarding failure analysis, the predominant failure mode observed in all repaired specimens was adhesive failure, under both static and fatigue testing conditions.

IV. CONCLUSIONS

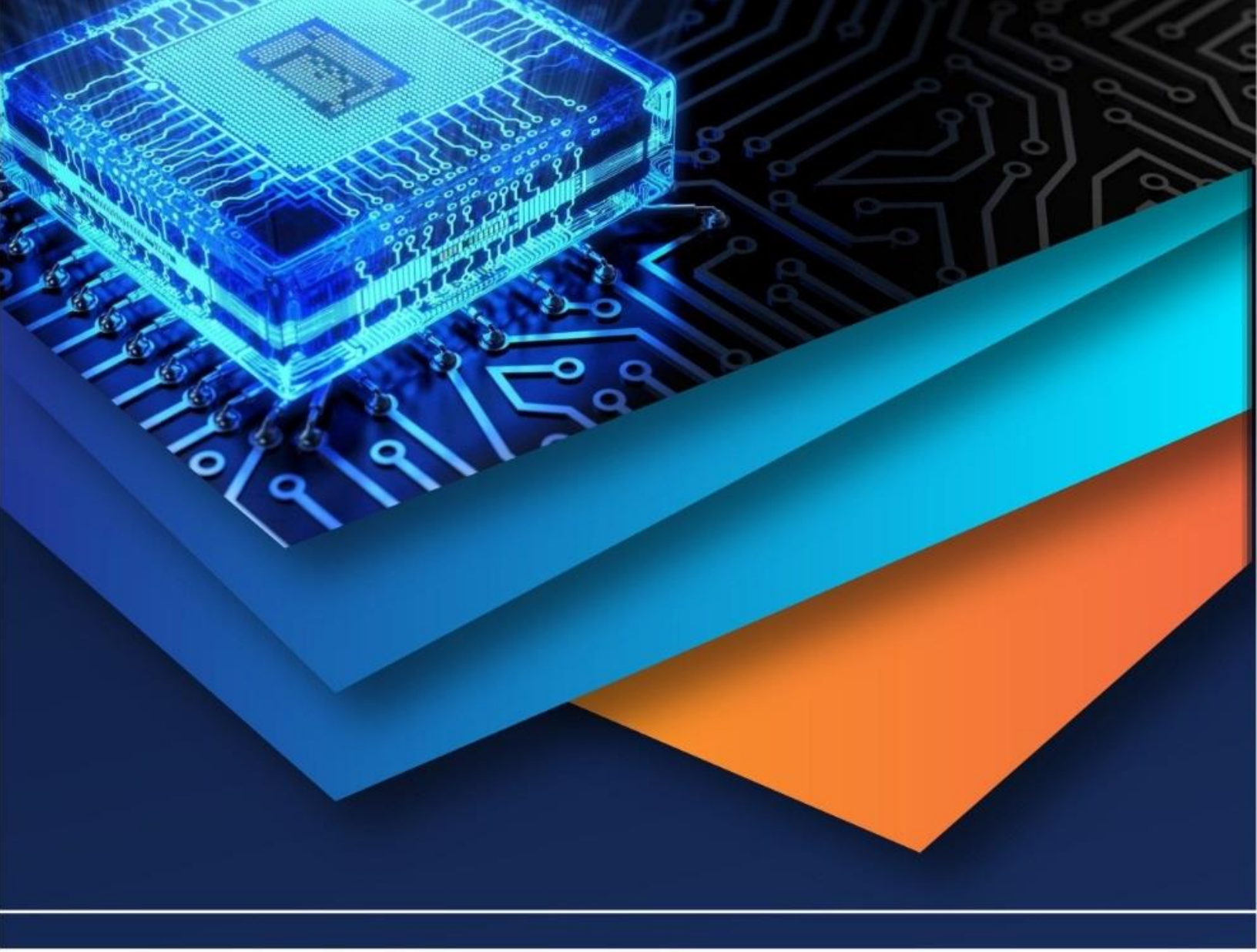
It is important to recognize that none of the repair techniques evaluated was able to completely restore the original strength of the CAD-CAM restorative material. Surface treatments involving diamond bur grinding, air-abrasion, and/or adhesive application yielded comparable results, regardless of the specific combination used. However, using silane alone is not advised, as it leads to low initial bond strength.

V. ACKNOWLEDGMENT

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