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Minimally invasive CAD/CAM lithium disilicate partial-coverage restorations show superior in-vitro fatigue performance than single crowns

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Abstract

Objective: To analyze the influence of restoration design (partial-coverage restoration vs. crown) and ceramic layer thickness on the performance and failure loads of CAD/CAM-fabricated lithium disilicate (LDS) reconstructions on molars after fatigue.

Materials and Methods: Seventy-two posterior monolithic CAD/CAM-fabricated LDS restorations (IPS e.max CAD, Ivoclar Vivadent) with different occlusal/buccal ceramic layer thicknesses (1.5/0.8, 1.0/0.6, and 0.5/0.4 mm) and restoration designs (PCR: non-retentive full-veneer/partial-coverage restoration, C: crown,) were investigated and divided into six groups ($n = 12$, test: PCR-1.5, PCR-1.0, PCR-0.5; control: C-1.5, C-1.0, C-0.5). LDS restorations were adhesively bonded (Variolink Esthetic DC, Ivoclar Vivadent) to dentin-analogue composite dies (Z100, 3M ESPE). All specimens were subjected to thermomechanical loading (1.2 million cycles, 49 N, 1.6 Hz, 5–55°C) and exposed to single load to failure testing. Failure analysis was performed with light and scanning electron microscopies. Data were statistically analyzed using ANOVA, Tukey-Test, and *t*-test ($p < 0.05$).

Results: Eight crown samples (C-0.5) and one PCR specimen (PCR-0.5) revealed cracks after fatigue, resulting in an overall success rate of 87.5% (crowns: 75%, PCRs: 96.88%). Direct comparisons of PCRs versus crowns for thicknesses of 0.5 mm ($p < 0.001$) and 1.0 mm ($p = 0.004$) were significant and in favor of PCRs. Minimally invasive PCRs (0.5 and 1.0 mm) outperformed crowns with the identical ceramic

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thickness. No difference was detected ($p = 0.276$) between thickness 1.5 mm PCRs and crowns.

Conclusions: Minimally invasive monolithic CAD/CAM-fabricated posterior LDS PCRs (0.5 and 1.0 mm) resulted in superior failure load values compared to minimally invasive crowns. Minimally invasive crowns (0.5 mm) are prone to cracks after fatigue.

Clinical Significance: Minimally invasive CAD/CAM-fabricated LDS PCR restorations with a non-retentive preparation design should be considered over single crowns for molar rehabilitation.

KEYWORDS
ceramics, computer-aided design, fatigue, full-veneer, partial-coverage restoration

1 | INTRODUCTION

Nowadays, the most frequent reconstructive treatment in the United States is still the single-tooth restoration with annual growth rates of up to 8% for single crowns worldwide.[1–3] In times of digital dentistry, the steadily evolving Computer-Aided Design (CAD)/Computer-Aided Manufacturing (CAM) technology leads to a trend toward monolithic restorations in all material classes.[4–7] Monolithic reconstructions fulfill the potential to avoid chipping and delamination problems, which are common in veneered bi-layer systems, while reducing tooth substance removal and production costs at the same time.[8–12]

Increased prevalence of severe tooth wear caused by biocorrosive defects, such as erosion, abrasion, attrition or combinations of these, especially in young patients, accelerated the development of minimally invasive treatment concepts.[13,14] To rehabilitate the posterior dentition in a minimal invasive approach, occlusal veneers evolved as the preferred treatment choice.[15–18] If defects additionally involve buccal and cervical areas, clinicians must choose between a full coverage-crown preparation or an occlusal restoration with an accessory Class V composite filling. Drawbacks of this treatment approach are the increased reduction of sound tooth structure for full-crown preparations and the reduced longevity of Class V fillings in the worn dentition.[19,20] Partial-coverage restorations (PCR) or so called "full-veneers", which include occlusal, labial and if necessary proximal areas offer a minimally invasive treatment alternative for such teeth.[21,22] With the benefit of superior esthetics in patients with a strong visibility of premolars and first molars, these PCRs may serve as an esthetic indirect restoration while preserving as much tooth substance as possible.[23,24] Moreover, social-network content and video-calls ("zoom-boom"), especially during the COVID-19 pandemic, have increased critical self-perception of one's own smile and outward appearance as well as the wish for esthetic self-improvement of patients.[25,26] A recent survey by the British Orthodontic Society underlies this: 62% of orthodontists recorded an increase in demand for esthetic treatments during COVID-19.[26]

Lithium disilicate glass-ceramics (LDS) offer superior esthetics[27,28] and a reliable clinical long-term survival.[29–31] The clinical performance of LDS CAD/CAM crowns is high, with survival rates of 93% after 6 years[32] and 80.1% after 15 years.[33] CAD/CAM-fabrication of LDS reconstructions provides a standardized manufacturing process and enables an improvement of cost and time effectiveness.[34] Nonetheless, the manufacturers' guidelines suggest a minimum restoration thickness of 1.0 mm for posterior crowns and partial-coverage restorations to avoid restoration fractures during clinical service.[34–37] Compared to traditional crown preparations with a recommended occlusal reduction of 1.5–2 mm, minimally invasive preparation designs require a less invasive tooth preparation.[38–41] LDS CAD occlusal veneers with an average occlusal reduction of 0.4–0.6 mm in the central groove and 1.0–1.3 mm at the cusp tips presented a survival rate of 100% after 3 years.[42] High survival rates of 96.49% after 16.9 years were also reported for LDS posterior crowns and partial-coverage restorations (IPS e.max Press) (≥1 or < than 1 mm).[31]

Yet, in-vitro literature is controversial if LDS CAD crowns with a minimally invasive layer thickness of 0.7–1 mm are clinically applicable.[4,39,43–45] The limited evidence of in-vitro studies, which are available on monolithic LDS (IPS e.max CAD and IPS e.max Press) crowns with a reduced layer thickness of 0.5 mm reported a high variability of failure loads (values between 369.2 ± 117.8 and 827 ± 318 N[34,46,47]). In contrast, minimally invasive LDS occlusal veneers (IPS e.max Press and IPS e.max CAD) showed extraordinary results in a systematic review on in-vitro and clinical studies.[15,48–50] Nevertheless, clear recommendations for a minimally invasive preparation design for cases in which defects involve occlusal as well as buccal or cervical areas are currently missing. Therefore, the aim of this in-vitro study was to evaluate the fatigue survival and failure load of CAD/CAM fabricated LDS standard (1.5 mm), thin (1.0 mm), and ultrathin (0.5 mm) PCRs compared to crowns on molars after thermomechanical loading. The research hypotheses were that (i) the restoration design (PCR vs. crown) and (ii) ceramic layer thickness would affect the failure load of posterior CAD/CAM LDS restorations.

2 | MATERIALS AND METHODS

In this in-vitro study a total of 72 specimens were randomly divided into two groups according to the type of restoration (Test: full-veneer/partial-coverage restoration (PCR) vs. control: crown (C)) and further subdivided according to occlusal/buccal ceramic layer thickness (0.5/0.4, 1.0/0.6, and 1.5/0.8 mm), resulting in subgroups of $n = 12$ specimens. The test-set up is displayed in Figure 1.

2.1 | Specimen preparation

To standardize test specimens, a maxillary first molar of a typodont model (frasaco-model, frasaco, Tettnang, Germany) was used to simulate a realistic clinical condition. Before preparation, two silicone impressions (TwinDuo, Picodent, Wipperfürth, Germany) were made to control tooth substance removal in a bucco-palatal and mesio-distal direction.

A single experienced prosthodontist performed the master die preparations for the type of restoration designs (PCR vs. crown) and different ceramic layer thicknesses (0.5, 1.0, and 1.5 mm). In total six master dies were prepared. Preparation was performed with a 4.5 optical enlargement, coarse and fine diamond burs (no. 370314 035, no. 8370314 035, no. 879314 012, and no. 8879314 012, Komet, Lemgo, Germany) at high speed and under constant air-water-spray cooling. The PCR preparation design was non-retentive (no occlusal/proximal box preparation) and involved occlusal, buccal, and proximal areas in the corresponding thickness (Group 0.5: 0.5/0.4 mm; Group 1.0: 1.0/0.6 mm; Group 1.5: 1.5/0.8 mm). To facilitate adhesive cementation and seating of PCRs two diagonal shallow notches (0.2 mm depth) were additionally prepared (Figures 2 and 3). The buccal area received a chamfer finish line in the respective thickness (Figure 3). The full-coverage crown preparation was performed accordingly without notches (Figure 3). Preparation depth was controlled with silicone keys and a periodontal probe.

To generate 72 dentin-analogue abutments, a resin-based composite (Filtek Z100, 3M ESPE, Neuss, Germany) with an elastic modulus of 18 GPa,[51] which is similar to that of human dentin with 16–18 GPa,[52] was chosen. Impressions of the six master dies were obtained with a polyvinylsiloxane material (Identium, Kettenbach,

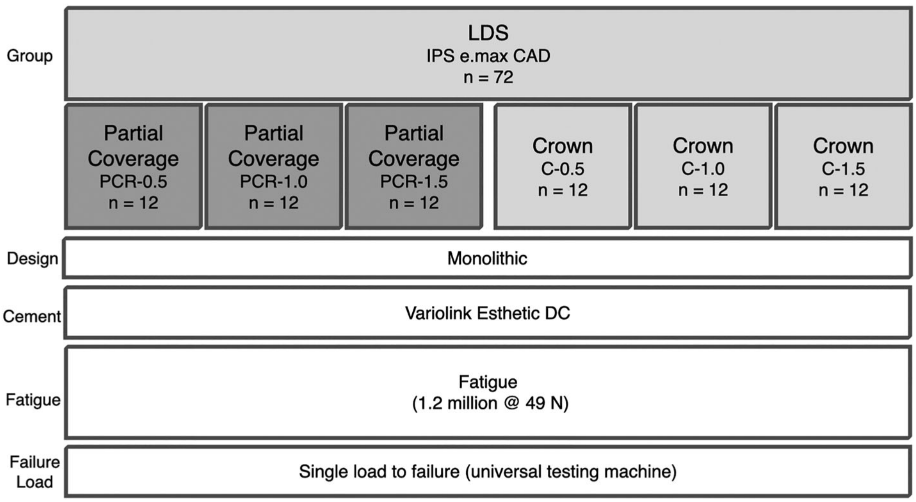

FIGURE 1 Test set-up.

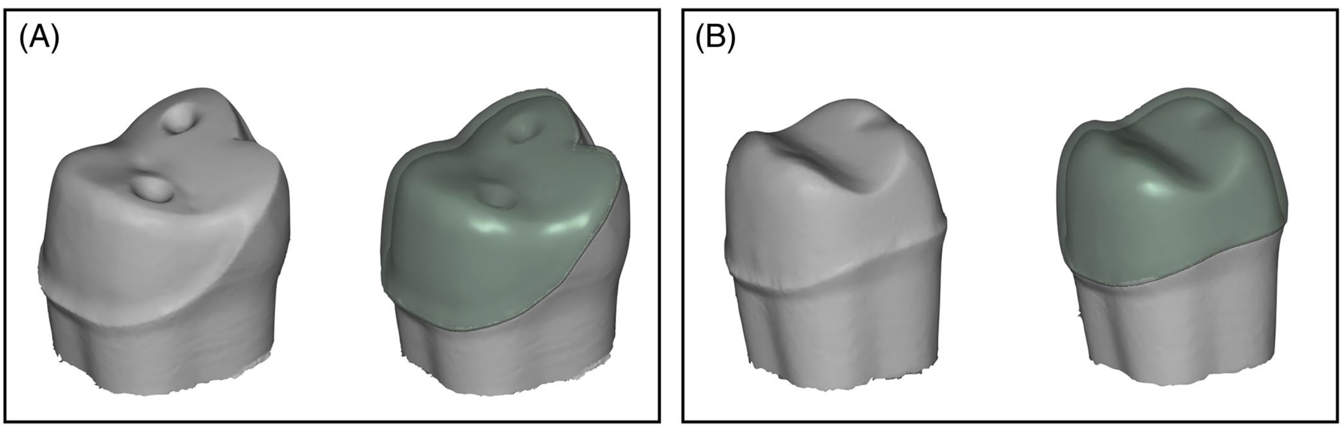

FIGURE 2 Preparation and restoration designs of (A) Full-veneer/Partial-coverage restoration and (B) Complete crown.

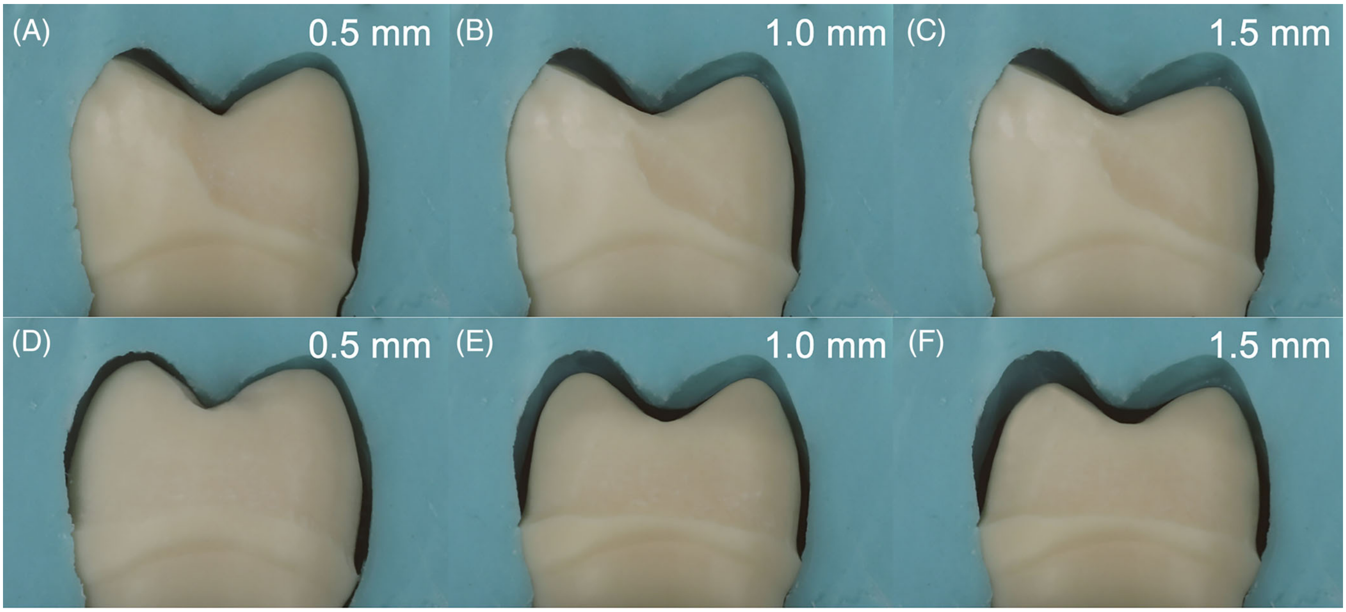

FIGURE 3 Preparation design of a maxillary first molar with respective silicon keys; (A–C) Non-retentive partial-coverage restoration. (A) Group 0.5 (occlusal 0.5 mm/buccal 0.4 mm); (B) Group 1.0, (1.0/0.6 mm) and (C) Group 1.5 (1.5/0.8 mm); (D–F) Complete crown restoration, (D) Group 0.5 (0.5/0.4 mm); (E) Group 1.0 (1.0/0.6 mm) and (F) Group 1.5 (1.5/0.8 mm).

Eschenburg, Germany). Consequently, the negative forms were filled with the resin-based composite in 1.5 mm thick layers and LED-light curing was conducted for 20 s (Bluephase G4 with 1200 mW/cm^2, Ivoclar Vivadent, Schaan, Liechtenstein). The dentin-like resin dies were then stored in distilled water at 37°C for 3 to 5 weeks in an incubator (Universalschrank UF55, Memmert, Schwabach, Germany) to allow hydration and continuous polymerization.[53] Subsequently, all resin dies were embedded in a self-curing epoxy resin (RenCast® CW20/ Ren® HY 49, Huntsman Advanced Materials, TX, USA) to imitate the elasticity of bone.[54,55]

2.2 | Fabrication of all-ceramic CAD/CAM restorations

The six master preparation dies were scanned in occlusion of the upper and lower typodont models using a laboratory scanner (PrograScan PS5, Ivoclar Vivadent). All reconstructions were designed with their respective thicknesses in a dental CAD software (exocad Dental CAD, exocad, Darmstadt, Germany). The virtual spacer was set at 50 μm. Datasets were calculated in a CAM software (PrograMill CAM Software, Ivoclar Vivadent) and milled out of partially crystalized lithium disilicate CAD/CAM blocks (IPS e.max CAD LT, Ivoclar Vivadent) in a five-axis milling machine (PrograMill PM7, Ivoclar Vivadent AG). Finally, crystallization and glazing of all restorations were performed (Programat EP 3010, Ivoclar Vivadent). All restorations were fabricated by the same master dental technician according strictly to manufacturer's recommendations. Before cementation, the restorations' thicknesses were verified with a caliper (Kroeplin GmbH, Schlüchtern, Germany).

2.3 | Adhesive cementation

Prior to adhesive cementation, the intaglio surfaces of all lithium disilicate restorations were etched with 4.9% hydrofluoric acid (IPS Ceramic Etching Gel, Ivoclar Vivadent) for 20 s and afterwards thoroughly rinsed with air-water spray and dried with oil-free air stream. Subsequently, a primer was applied for 60 s (Monobond Plus, Ivoclar Vivadent).

Resin dies were first pretreated with pumice powder (Picodent, Wipperfürth, Germany), rinsed with air-water spray, dried with an oil-free air stream, and cleaned with 70% ethanol. Afterwards dentin-analogue abutments were pretreated with a light-curing dental adhesive (Adhese Universal, Ivoclar Vivadent). The adhesive was applied for 20 s on the surface of the resin die, gently air-dried and light-cured for 20 s (Bluephase G4 with 1200 mW/cm^2, Ivoclar Vivadent).

All pretreated restorations were then adhesively bonded with a dual-curing composite cement (Variolink Esthetic DC, Ivoclar Vivadent) to the resin dies. Excess cement was carefully removed with foam pellets and LED light-curing was performed for 20 s from each side (Bluephase G4, Ivoclar Vivadent) under oxygen protection (Liquid Strip, Ivoclar Vivadent). Specimens were then again stored in distilled water for 24 h at 37°C in an incubator (Universalschrank UF55) to allow further polymerization of the adhesive interface before fatigue testing.[56]

2.4 | Fatigue analysis

All specimens were subjected to cyclic mechanical loading with simultaneous thermocycling (5–55°C in distilled water, dwell time 120 s) in a mouth motion fatigue simulator (CS 4.8 professional line, SD Mechatronik, Feldkirchen-Westerham, Germany) (Figure 4). An occlusal load of 49 N was applied to the disto-palatal cusp of the restoration for 1.2 million chewing cycles at a frequency of 1.6 Hz. To simulate aspects of natural mastication, steatite spheres ($r = 3$ mm, Hoechst CeramTec, Wunsiedel, Germany) were moved 0.5 mm horizontally downwards from the disto-palatal cusp to the central fissure.[57,58] This in-vitro test-set up is reported to simulate 5-years of clinical behavior under artificial conditions.[59–61] Specimens were vertically positioned and loaded without angulation. During thermodynamic loading, specimens were visually inspected, aided by a transilluminating crack detection probe (DIA Stick, I.C. Lechner GmbH & Co KG, Stockach, Germany), for cracks, fractures, or debonding twice a day. A survival and success rate after dynamic loading was computed. Specimens, which were unscathed after fatigue were rated as success and samples with evident cracks or debonding, but still in function (in situ) were rated as survival. Samples with catastrophic bulk fractures (fractures where the entire ceramic restoration was fractured and split into two or more pieces) were rated as non-survival.[15,62,63]

2.5 | Single-load-to-failure testing

After fatigue, all specimens were subjected to a single cycle load-to-failure test (SLF) in a universal testing machine (Zwick Z010/TN2S, Zwick Roell, Ulm, Germany) (Figure 5). Load was applied through a steel ball with a diameter of 6 mm, which was aligned at the same contact point as during thermomechanical fatigue. The vertical cross-head speed was set at 1.5 mm/min. A video camera was placed to observe all specimens during SLF testing and to follow possible failure evolution of samples. Failure was defined as either a visible crack or fracture or a 20% drop in the maximum load (F_{max}) without an obvious event. Specimens were axially loaded until a failure occurred and the maximum load-to-failure force was recorded with the corresponding test software (TextXpert III, Zwick Roell).

2.6 | Failure analysis

Samples were first analyzed using a polarized light microscope (AxioZoom V.16, Zeiss, Oberkochen, Germany) to determine the mode of failure and fracture origin. Z-stack mode (ZEN Core 3.3, Zeiss) was used to gather multiple images with different depths and merge layers within the same image to increase the depth of field.

Most representative fracture types were further subjected to qualitative fractographic analysis using environmental scanning electron microscopy (Quanta 600 FEG ESEM).

2.7 | Statistical analysis

A power calculation (G*Power 3.1.9.7, Düsseldorf, Germany) for a 2×3 factorial design with factors (i) restoration design (PCR vs. crown) and (ii) ceramic layer thickness (0.5, 1.0, and 1.5 mm) was performed with respect to statistical testing via ANOVA. A sample size of $n = 12$ per group ($n = 72$ in total) was determined to enable detecting effects of at least medium size (Cohen's effect size of $f = 0.26$) with 80% power and a two-sided type-I error of $p < 0.05$ for the two factors and their interactions.

Data were statistically analyzed with SPSS 28 (IBM Corp., Armonk, NY, USA). The Levene Test was applied to test for homogeneity of variance before using ANOVA to test for main effects and interactions of the two factors of interest (restoration design and ceramic layer thickness). The influence of ceramic layer thickness was further analyzed post-hoc using Tukey tests following separate one-way ANOVAs per restoration design. The influence of restoration design was separately analyzed post-hoc for each layer thickness level via two-sample t-tests. The level of significance was set at $p < 0.05$ (95%-CI) for all tests. Data were graphically presented in boxplots.

3 | RESULTS

3.1 | Cyclic fatigue loading

All restorations showed wear scars in the contact area after fatigue exposure, as a result of the movement of the steatite ball during cyclic mechanical loading. The overall survival rate was 100% for all lithium disilicate reconstructions. No debonding of reconstructions occurred during or after dynamic fatigue loading, but not all specimens withstood fatigue application unscathed. Eight crowns of Group C-0.5 (after 35,025, 2× 43,757, 112,196, 386,388, 396,393, 444,262, and 901,591 cycles) and one restoration of Group PCR-0.5 (after 362,856 cycles) showed evident cracks after fatigue (Figure 7).

The overall success rate yielded in 87.5%. The success rate for PCRs was 96.88% and for crowns 75%. The success rates of PCRs and crowns according to ceramic layer thickness are displayed in Table 1.

3.2 | Single load to failure

The results obtained from the SLF testing are summarized in Table 2 and graphically displayed in Figure 6.

Both restoration design (PCR vs. crown) and ceramic layer thickness (0.5 mm vs. 1.0 mm vs. 1.5 mm) showed significant main effects with respect to failure load (preparation design: $F(1.66) = 19.76$, $p < 0.001$, thickness: $F(2.66) = 22.91$, $p < 0.001$). However, a statistically significant interaction between the two factors (restoration design and ceramic layer thickness) could not be detected ($F(2.66) = 1.24$, $p = 0.296$).

Regarding the comparisons of ceramic layer thickness levels separately for each restoration design, post-hoc Tukey tests revealed significant differences for crowns, which were in favor of thicker crowns compared to thinner crowns (C-0.5/C-1.0 $p = 0.005$, C-0.5/C-1.5 $p < 0.001$, C-1.0/C-1.5 $p < 0.001$). However, no significant differences were detected for layer thicknesses of PCRs (PCR-0.5/PCR-1.0

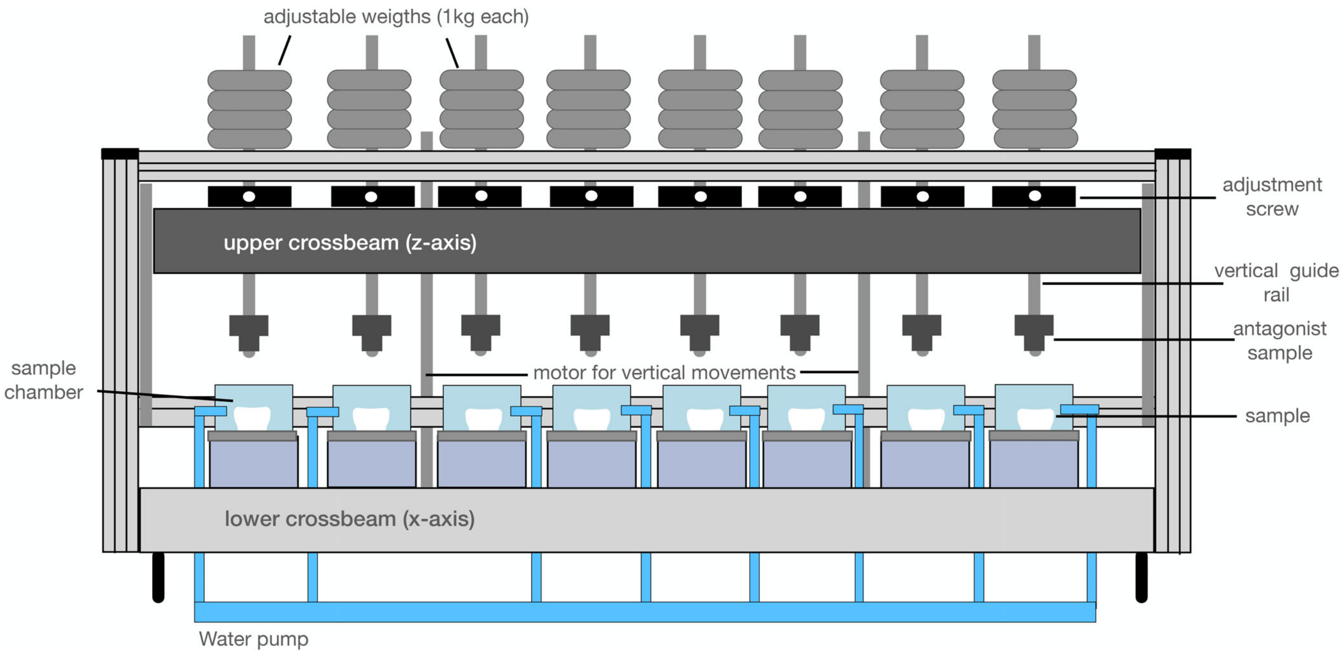

FIGURE 4 Schematic drawing of the fatigue simulator (CS 4.8 professional line, SD Mechatronik, Feldkirchen-Westerham, Germany) with eight sample chambers and simultaneous thermocycling. A total load of 5 kg (=equals 49 N) was applied to the samples, as the vertical guide rail and the sample holder weight together another 1 kg.

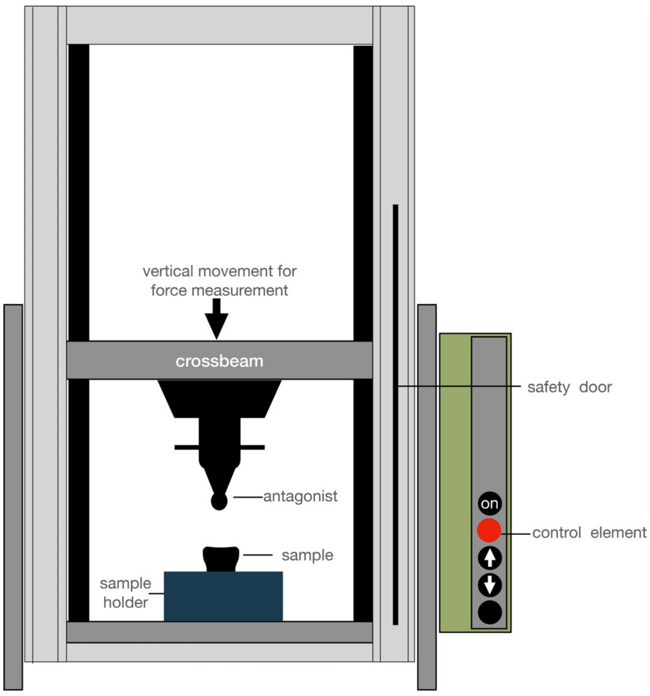

FIGURE 5 Schematic drawing of the universal testing machine (Zwick Z010/TN2S, Zwick Roell, Ulm, Germany) for single cycle load-to-failure testing (SLF).

$p = 0.283$, PCR-1.0/PCR-1.5 $p = 0.277$), aside from the direct comparison for ceramic layer thicknesses of PCR-0.5 and PCR-1.5 where a significant difference in favor of the standard (1.5 mm) thickness ($p = 0.011$) was observed.

Post-hoc *t*-tests for separate comparisons between restoration designs for each level of ceramic layer thickness with respect to restoration design (PCR vs. C) revealed significant differences for thicknesses of 0.5 mm (C-0.5/PCR-0.5: $t(22) = -4.11$, $p < 0.001$) and 1.0 mm (C-1.0/PCR-1.0: $t(15.43) = -3.18$, $p = 0.006$) in favor of PCRs. PCRs with a minimally invasive design and layer thickness outperformed crowns with the identical ceramic thickness. No statistically significant difference between PCRs and crowns was found for a 1.5 mm ceramic layer thickness (C-1.5/PCR-1.5: $t(22) = -1.12$, $p = 0.276$).

3.3 | Failure and fractographic analyses

Failure analysis after fatigue revealed seven samples of Group C-0.5 and one sample from Group PCR-0.5 with radial cracks starting from the intaglio cementation surface beneath the contact point during cyclic loading. The radial cracks spread sideways and upwards. In C-0.5 crowns, radial cracks penetrated through the ceramic layer and progressed relentlessly around the lateral walls under the influence of slow crack growth during moist cyclic loading (Figure 7C,D).[10,11] However, the radial crack in sample PCR-0.5 remained contained within the ceramic layer (Figure 7A,B). In one sample of Group C-0.5, hoop stresses along the axial walls of the crown lead to crack formation during fatigue.[36]

After SLF predominately catastrophic ceramic bulk fractures of both PCRs and crowns with involvement of the dentin-analogue dies for thickness of 1.5 and 1.0 mm into 2–3 main fragments were observed. Groups PCR-1.5, PCR-1.0, and C-1.5, showed exclusively

TABLE 1 Success rates after simulated fatigue exposure of 5 years.

Group	Intact and unharmed specimens after fatigue	Success rate	Success rate of restoration design	Overall success rate
PCR-1.5	12/12	100%	PCRs 96.88% 35/36	87.50%
PCR-1.0	12/12	100%		
PCR-0.5	11/12 (one crack after 362,856 cycles)	91.66%		
C-1.5	12/12	100%	Crowns 75.00% (28/36)	
C-1.0	12/12	100%		
C-0.5	4/12 (eight cracks after 35,025 cycles, 2× 43,757 cycles, 112,196 cycles, 386,388 cycles, 396,393 cycles, 444,262 cycles and 901,591 cycles)	33.33%		

TABLE 2 Failure load results of all tested groups [N = Newton].

Group name	Min	1st Qu	Median	Mean	3rd Qu	Max	SD
PCR-1.5	2210	2386	2660	2883	3380	4990	782
PCR-1.0	1340	2041	2370	2451	2861	3640	646
PCR-0.5	1400	1645	1840	2023	2400	3260	594
C-1.5	1560	2186	2500	2566	2946	3650	598
C-1.0	1400	1610	1775	1798	1986	2290	296
C-0.5	708	959	1165	1193	1428	2010	369

Note: 1st Qu = 25% of data was below this value; Median = 50% of data was below this value; 3rd Qu = 75% of data was below this value.
Abbreviations: Max, maximum; Min, minimum; SD, standard deviation.

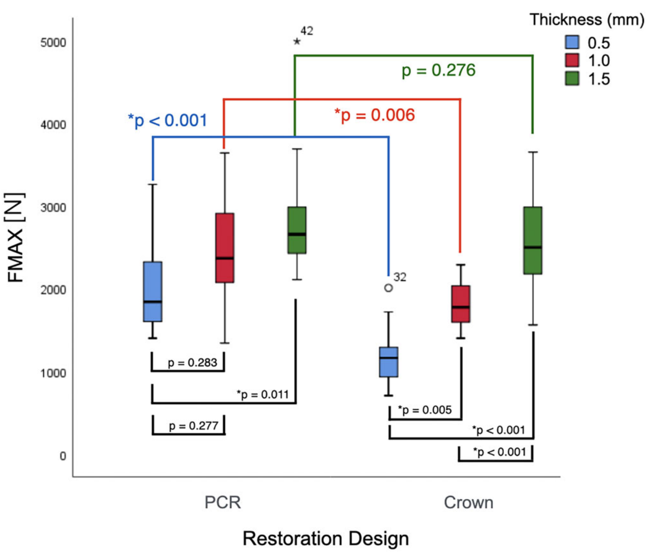

FIGURE 6 Boxplot of Failure Loads (F_{max} in N) of tested Groups (* indicates outlier for Group PCR-1.5 and 0 indicates outlier for Group C-0.5). Statistical significance ($p < 0.05$) is indicated by asterisk in front of p-value.

catastrophic ceramic bulk fractures (100%) with involvement of the resin abutment die (PCR-1.5: 83.3%, PCR-1.0: 75%, C-1.5: 100%), whereas Group C-1.0 showed mainly ceramic bulk fractures (83.3%) and two ceramic fractures with partial detachment of the crown (16.7%) and an intact die. Samples of Group PCR-0.5 and C-0.5 revealed both mixed catastrophic ceramic bulk fractures (PCR-0.5: 50%, C-0.5: 33.3%) and extended "chipping" fractures within the ceramic (PCR-0.5: 50%, C-0.5: 66.6%) after SLF.

Resin dies remained intact more frequently with a thinner thickness of 0.5 mm (PCR-0.5: 75%, C-0.5: 83.3%), compared to thicker thicknesses of 1.0 mm (PCR-1.0: 25%, C-1.0: 25%), and 1.5 mm (PCR-1.5: 16.7%, C-1.5: 0%).

During detailed fractographic analysis, telltale markings were observed, comprising hackle and arrest lines, which may allow to determine the origin of fracture.

A detailed fractographic analysis of representative specimens of each Group is presented in Figures 8 and 9.

4 | DISCUSSION

The present laboratory study aimed to analyze the influence of restoration design and ceramic layer thickness on fatigue and fracture resistance of posterior monolithic CAD/CAM LDS restorations. The tested research hypotheses were accepted, as both restoration design and ceramic thickness showed significant effects on failure loads.

Clinically, maximum masticatory forces in a range of 289–700 N have been reported for the posterior dentition.[14] Regardless of restoration design and ceramic layer thickness all specimens withstood this occlusal load threshold with mean failure load values of 1193–2883 N. Although not all of the specimens (especially for Group C-0.5) withstood dynamic loading unscathed, all samples were still in

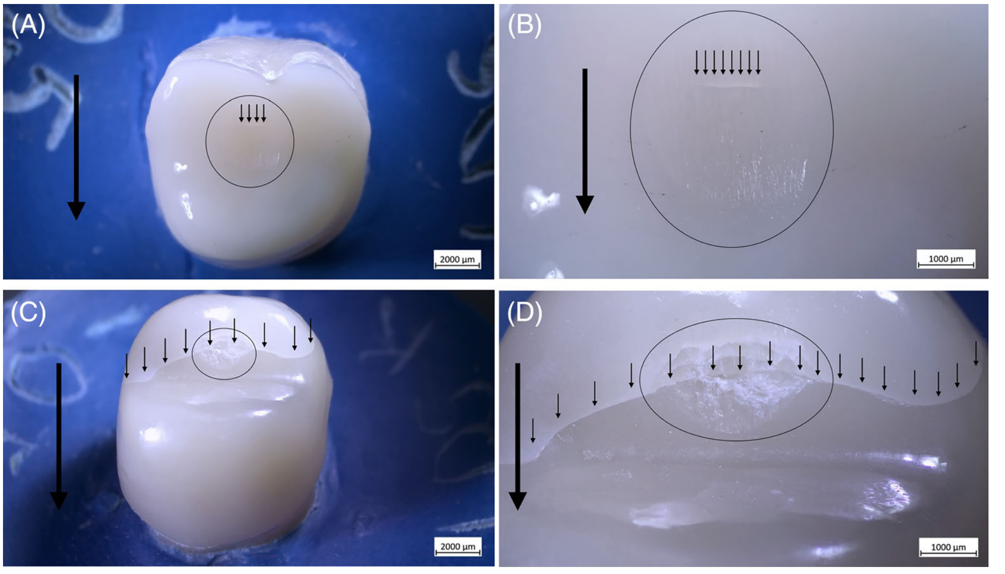

FIGURE 7 CAD/CAM LDS restorations revealing cracks (small arrows) and wear (circle) after fatigue. Bold arrow indicates direction of sliding movement during fatigue. (A + B): PCR-0.5; (C + D) C-0.5.

function and therefore subjected to single load to failure testing as in previous studies.[24,50,62,63] So far, neither clinical studies nor laboratory investigations could show that pre-damaged reconstructions exhibit a shorter service life or failure loads than non-damaged restorations.[29,48,63] A possible explanation might be that resulting cracks, depending on their locations, may require much larger driving forces to propagate across an anatomic restoration.[6] This behavior is similar to cracks observed in human enamel, which do not necessarily result in an immediate increase in failure rates of the compromised teeth.[37,63]

The success rates of PCRs and crowns were 96.88% and 75%. A systematic review of clinical studies, which compared onlays and full-coverage crowns confirmed high survival rates of 93.5% and 95.38% with no statistical difference between the groups after five years.[40] Another recently published review with meta-analysis, found equally survival and success rates for both treatment options of onlays/partial crowns and complete crowns after one and 3 years of service.[41] Clinical long-term studies of heat pressed and CAD/CAM-fabricated monolithic LDS crowns, occlusal veneers with a shoulder preparation and partial-coverage restorations reported also high survival rates of 80.1%–96.75% after 15–16.9 years, 100% after 11–13 years and 95.27% after 16.9 years of function.[29,31,33,48]

The results of the present in-vitro study showed that PCRs revealed higher failure load values compared to complete coverage crowns. Minimally invasive PCRs outperformed the corresponding full-coverage crowns with the identical layer thickness for ultrathin (0.5 mm) and thin (1.0 mm) reconstructions. For standard thick restorations (1.5 mm), the restoration design does not seem to have a significant influence on failure loads. A possible explanation might be due to the complexity of the different restoration designs, as any loss of tooth structure weakens the tooth-restoration system.[21]

Direct comparisons to previously published in-vitro studies in the literature are difficult, since the investigated preparation design of full-veneers on molars has not been analyzed elsewhere. Moreover, methodological differences in study set-ups and fatigue protocols can highly impact the outcome of obtained fracture strength values.[16]

Equivalent failure load values for CAD/CAM fabricated 1.0 mm LDS occlusal veneers with a rounded shoulder or a minimally invasive chamfer of 2395 and 2408 N were recorded after simulated artificial aging (1.25 million cycles, 50 N, 1 Hz).[17] A study which compared standard thickness (1.5 mm) CAD/CAM LDS molar crowns to two overlay designs with a chamfer, observed lower fracture forces of 1018 N for crowns and 436–813 N for the overlays.[23] However, specimens were subjected to a higher load of 275 N and a higher number of loading cycles (2 million, 1 Hz) during aging.[23]

Monolithic CAD/CAM fabricated LDS molar crowns were also tested in different ceramic layer thicknesses (0.5–1.5 mm) and various fatigue protocols.[28,34,39,47]

Lower and partly unsatisfactory failure load values of 470 N (without fatigue) and 369 N (with fatigue) for 0.5 mm, 801 N (without fatigue) and 889 N (with fatigue) for 1.0 mm, 1107 N (without fatigue) and 980 N (with fatigue) for 1.5 mm LDS molar crowns were observed with a similar aging protocol (1.2 million cycles, 108 N).[47] Yet, the study loaded the specimens in a 30° angle, perpendicular to one cusp and with a higher load during fatigue (108 N) which might explain the lower fracture values.[47] Two studies where no cyclic fatigue protocol was applied recorded lower failure load values of 827 N (0.5 mm), 1228 N (0.7 mm), 1503 N (1.0 mm) and 1440–1499 N (1.5 mm) for non-aged monolithic CAD/CAM LDS crowns as in the present study.[34,39] The same resin material (Z100) was used as an abutment in one of the studies simulating the elastic modulus of dentin as in the present investigation.[39] A study with a prolonged fatigue application (5 million cycles, 275 N) lead to slightly lower failure load values of 980 N (0.8 mm), 1162 N (1.0 mm) and 1540 N (1.5 mm) compared to the obtained results of the present study.[28]

Ceramic bulk fractures are still the most common complication for onlays, PCRs, and crowns in clinical observations.[40,41] Failure modes after SLF revealed more bulk fractures with involvement of the

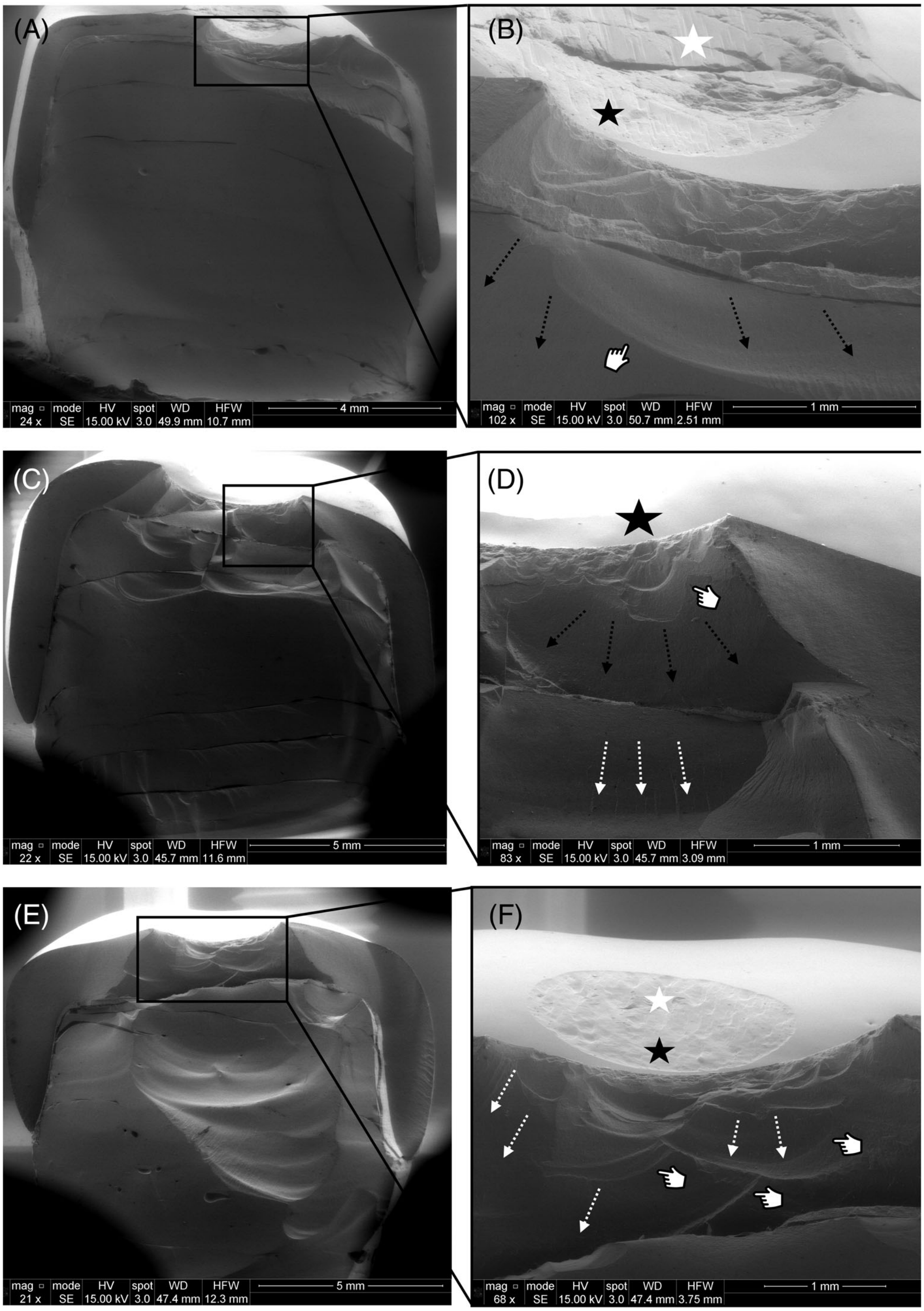

FIGURE 8 Representative scanning electron microscopy (SEM) micrographs of fractured monolithic LDS crowns of C-0.5 (A, B), C-1.0 (C, D) and C-1.5 (E, F). (A, C) and (E) are overviews of the respective LDS crowns and (B, D, F) detailed pictures showing the indentation area (black asterisks) and origin that lead to bulk fracture of the crown with involvement of the underlaying resin die. (B) shows sample C-0.5 (same as in Figure 5C,D), with crack (white asterisk) that was already present during fatigue. Dotted lines showing the direction of crack propagation; several arrest lines are visible (pointer) with their concave portion directing toward the origin of failure from the loading area. (D) is a magnification of a specimen from Group C-1.0 where several arrest lines (pointer) and hackle lines (white dotted lines) are visible, which indicate the direction of crack propagation (black dotted lines) from the occlusal surface toward the margins. In (F) surface wear of C-1.5, which occurred during fatigue from the steatite sphere (white asterisk), origin of failure (black asterisk), arrest lines (pointer) and hackle lines (white dotted lines) are clearly apparent.

resin die for thicker layer restorations (both 1.5 and 1.0 mm), whereas with ultrathin (0.5 mm) restorations, failures where restricted to cohesive ceramic fractures without involvement of the dentin-analogue abutment. Accordingly, thinner restorations could provide a “stress shielding protection” for the underlying tooth structure if failure occurs, while thicker restorations could possibly damage the abutment. If the restoration needs to be renewed, this could be beneficial, since tooth substance will be preserved. Other in-vitro studies with minimally invasive LDS restorations on human premolars and molars confirmed the observed failure modes with mainly cohesive ceramic fractures without involvement of the tooth for thin restorations.[24,49]

In depth fractographic analysis with telltale markings such as hackle lines and compression curls showed that the fracture origin after SLF started for both types of restorations mainly from the loading area. The loading area is the site that had the worst combination of tensile stresses and flaw severity, which then ultimately lead to fracture.[11] The evolution of restoration failures occur as a damage competition and accumulation, either resulting from repetitive loading and crack initiation during fatigue or as a result of mechanical overload during SLF.[11]

Limitations of the present study could be related to the use of composite dies instead of human teeth. This did not allow the

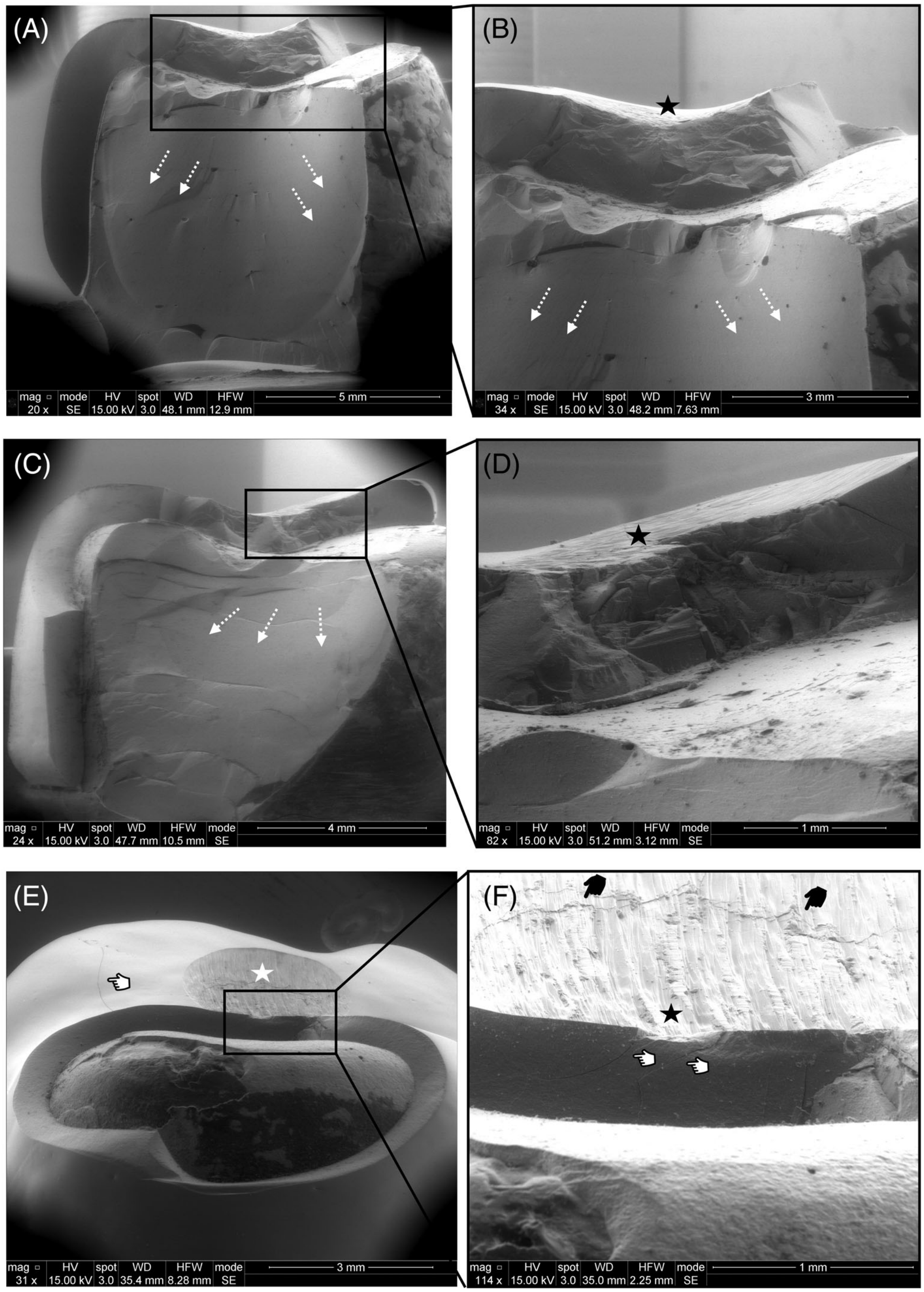

FIGURE 9 Representative SEM pictures of fractured monolithic LDS PCRs of Groups PCR-1.5 (A, B), PCR-1.0 (C, D) and PCR-0.5 (E, F). (A, C) and (E) are overviews of the respective PCRs and (B, D, F) detailed micrographs showing the indentation area (black asterisks) and origin of failure. Specimens of Group PCR-1.5 (A, B) and Group PCR-1.0 (C, D) showed a complete bulk fracture with involvement of the resin abutment, where hackle lines (white dotted lines) indicate the direction of crack propagation. Black asterisk indicates the loading area that lead to fracture of the restoration. (E) and (F) display the same sample of Group PCR-0.5 as in Figure 5A,B with partial detachment of the restoration and "chipping fracture". White asterisk describes the loading area with radial crack (black pointer) occurred during cyclic fatigue loading. (F) is a magnification of (E) where the white pointers highlight cracks initiating at the occlusal surface and propagating downwards to the cementation surface and resin die, eventually leading to cohesive "chipping" fracture.

investigation and impact of enamel and dentin as a bonding substrate on the load to failure and fatigue behavior of the monolithic LDS PCRs and crowns. However, the utilization of dentin-analogue abutments enabled a high standardization and a systematic analysis of the restorations, without variances in size, age and storage of human teeth. Moreover, a mid-term fatigue protocol was applied instead of long-term fatigue (up to 5 million cycles), which could have potentially led to more cracks or even bulk fractures during cyclic loading. Yet, the employed technique is nevertheless described to be sufficient to detect early failures of reconstructions and widely used in the dental literature.[3,60]

Since zirconia is presently promoted for minimally invasive tooth-borne restorations, future studies should consider and investigate the proposed restoration design of a full-veneer for this material as well.[7,12,18] Especially translucent zirconia and multilayer strength-gradient zirconia materials could be interesting candidates for monolithic and minimally invasive posterior reconstructions.

To the best of our knowledge this is the first laboratory study, which systematically investigated the proposed full-veneer/partial-coverage design with monolithic CAD/CAM fabricated LDS restorations on molars with different ceramic layer thicknesses. Full-veneer restorations can be a valuable addendum in the rehabilitation of posterior dentition, especially for full-mouth cases, caused by advanced tooth wear or bio-corrosive defects. Occlusal and cervical defects that need to be restored can be combined in a minimally invasive single all-ceramic restoration.[24]

The results of this in-vitro study highlight the superior mechanical performance of minimal invasive full-veneers in comparison to single crowns. Minimally invasive full-veneers should be given preference over full-coverage crowns, whenever possible according to defect configuration. However, it must be noted that manufacturer's recommended minimum layer thickness of adhesively luted LDS crowns is 1.0 mm.

Three-dimensional extended finite element analysis (XFEM) might further enlighten the difference in stress distribution and crack propagation behavior in full-veneers and their beneficial mechanical behavior in comparison to crowns.[6] Moreover, clinical trials in a prospective or randomized setting are needed to confirm the results of this in-vitro study.

5 | CONCLUSIONS

Based on the results of this in-vitro study, it was concluded that:

The restoration design (partial-coverage restoration vs. crown) and the ceramic layer thickness (1.5, 1.0, and 0.5 mm) affected the failure load of posterior CAD/CAM lithium disilicate restorations.

Minimally invasive full-veneers resulted in higher failure load values than full-coverage restorations.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they do not have any financial interest in the companies whose materials are included in this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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