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RESEARCH ARTICLE

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Shrinkage-induced cuspal deformation and strength of three different short fiber-reinforced composite resins

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Abstract

Objective: The aim of this study is to assess the shrinkage-induced cuspal deformation and strength of large MOD restorations using three different short fiber-reinforced composite resins (SFRC).

Materials and Methods: Twenty-seven typodont teeth #30 (Columbia) received a standardized slot-type preparation (5-mm by 5-mm depth and bucco-palatal width). Three types of SFRCs (everX Posterior, everX Flow, and a 50/50 mixture of both materials) were used with the Optibond FL bonding system. The intercuspal distance of each specimen ($n = 9$) was measured after preparation, immediately after restoration and at 3, 18, and 24 h. Each specimen was then subjected to simulated mastication (30° angulation with cyclic loading of buccal cusp at 5 Hz), starting at 100 N with 100 N increase every 100 cycles until fracture. Failure mode was determined as re-restorable versus nonrestorable failures. Cusp deformation data were analyzed by two-way repeated measures ANOVA and the fracture performance by Kaplan–Meier survival analysis.

Results: Shrinkage-induced cuspal deformation ranged from 27–34 microns (immediately) to 33–43 microns (24 h). The largest deformations were observed for everX Flow and the 50/50 mixture (up to 43 microns at 24 h), which also demonstrated the lowest average strength (1456 to 1511 N). everX Posterior demonstrated the least amount of shrinkage-induced cuspal deformation (27 microns, up 33 microns at 24 h) and the higher average strength (1744 N). everX Flow tended to demonstrate more repairable partial fractures while everX Posterior induced mainly catastrophic failures.

Conclusions: Large direct MOD restorations were most favorably restored with everX Posterior (less shrinkage, higher strength) at the expense of failure mode. everX Flow induced more friendly failure modes but more shrinkage-induced cuspal deformation.

Clinical Significance: When a low-cost restoration must be chosen, EverX Posterior will significantly improve the performance but not the failure mode of directly layered restorations. Because of its increased shrinkage values, everX Flow is best indicated as a limited liner to cover the IDS layer and improve geometry for semi-(in) direct restorations.

KEYWORDS
cusp deformation, fatigue resistance, short fibers, shrinkage stress

1 | INTRODUCTION

Large direct posterior restorations require mastering of shape, contours, occlusal anatomy, and function.[1,2] The dilemma of polymerization shrinkage,[3,4] and shrinkage stresses constitute additional daily challenges faced by dental professionals. When a successful adhesive protocol is used, the shrinkage can cause cuspal deformation and enamel cracks at the cusp base.[5,6] Hence, reduction of contraction stresses should be a priority in selecting the appropriate direct techniques.[7]

Various approaches have been proposed to manage shrinkage, such as elaborate layering techniques,[8] sandwich approaches using glass ionomer bases,[9] and fiber meshes,[10] in addition to delayed and slow-start light polymerization protocols.[11] It important to note, however, that most of the shrinkage stress develops during and after the vitrification stage and keeps progressing in the absence of light. Thus, the relaxation of the stress is limited when considering the time scales proposed for the soft polymerization protocols[12] and for the conversion rate to be clinically adequate. In other words, slow-start polymerization should be so slow that the resin would end up being unable to polymerize to an acceptable conversion rate.

The use of glass ionomer bases in the open and closed sandwich restorations can help minimize the shrinkage stress, and even more so with the use of the new "super-closed" technique, in which the volume of shrinking material is reduced significantly.[9] Layering techniques were also believed to help but do not necessarily have the ability to reduce shrinkage stresses[13,14] and might even yield worse results compared with bulk filling.[15] This is because of the V-factor of the restoration,[16] the amount of which can be related to the volume of the restoration and will increase with the distance between the most remote points of the cavity. Even when "stress-reducing" techniques are used (sophisticated layering, irradiation modes, and etc.), a large restoration will still generate major deformation. Factors influencing stress development are extremely complex (conversion rate, shrinkage, elastic modulus, shape, boundary conditions, and etc.) and the context that generates stresses should be always considered, including volume and size. Reducing the V-factor is a valid approach. It can be achieved by introducing nonshrinking components ("megafillers") such as conventional GIC in the sandwich technique, prepolymerized inserts, or using semi-(in)direct and indirect techniques (inlays). During the past decade, manufacturers have started to focus on simplifying direct techniques by proposing bulk filling materials. Among them, a short fiber-reinforced composite (SFRC) was introduced for high-stress bearing areas in 2013 (EverX Posterior, GC, Leuven, Belgium).[17] It offers a combination of flexural modulus and fracture toughness that is unique within the group of bulk-fill materials (12.6 GPa and 2.6 MPa $m^{1/2}$, respectively). It can be used in 4-mm deep increments, and can potentially match the toughness of dentin.[18,19] In a large MOD defect, it can possibly improve the performance of direct restoration to the same level as a CAD/CAM indirect restoration.[20] Due to the high viscosity (5%–15% content by weight of 0.017 by 0.8 mm e-glass fibers) and limited esthetics of everX Posterior, the manufacturer came up with a flowable version in 2019. The new product, called everX Flow[21] is designed to address the various challenges that face the users such as workability (low viscosity) and esthetics (dentin color). Due to the smaller size of its e-glass fibers (0.006 by 0.14 mm), the flow version has a higher content of fibers (25% by weight) than its predecessor. It was also presented with a better fracture toughness (2.8 MPa $m^{1/2}$) but lower flexural modulus (9.0 GPa) than everX Posterior. Yet, its shrinkage stress is still higher than its precursor.[22] In large MOD restorations, however, absolute control over the stresses can only be achieved through the use of indirect techniques,[8,23] thus significantly lowering the V-factor and limiting the shrinkage stress to the very thin layer of luting material. CAD/CAM materials are the main tenet of this approach due to their wear properties, color integration, fast processing, and millability in thin layers.[24,25,26,27,28]

The last decade, however, has been marked by challenging economy, inflation, and economic uncertainty. Hence there has been a rise in the demand and popularity of affordable restorations. Contemporary composites resins for direct restorations and the use of SFRC as dentin replacement material in large restorations have the potential of fulfilling this demand. Thus, this work assessed the cuspal deformation (shrinkage induced) and comparative strength of MOD direct SFRC of molars with three different types of formulations (everX Posterior, everX Flow, and 50/50 mixture). The null hypotheses were that (1) no significant differences would be found in cuspal deformation, and (2) there would be no significant difference in strength and failure mode between the three groups.

2 | MATERIALS AND METHODS

Twenty-seven identical plastic teeth (Typodont Tooth #30, Columbia, San Dimas, CA) received a standardized MOD preparation and were then restored in bulk with either (1) flowable fiber-reinforced composite resin (everX Flow; GC), (2) packable fiber-reinforced composite resin base (everX Posterior; GC), and (3) 50/50 mixed fiber-reinforced composite resin bases (everX Flow, everX Posterior, GC). The mixture was prepared in advance by combining equivalent amounts of everX Posterior and Flow, stacking them, pressing them flat and repeatedly folding and pressing them together using a vibrating spatula (Microvibes, Smileline, St. Imier, Switzerland) until a smooth paste was obtained.

The intercuspal distance was measured immediately after preparation, after restoration, as well as at 3, 18, and 24 h following the restoration. All specimens were then subjected to a cyclic load test.

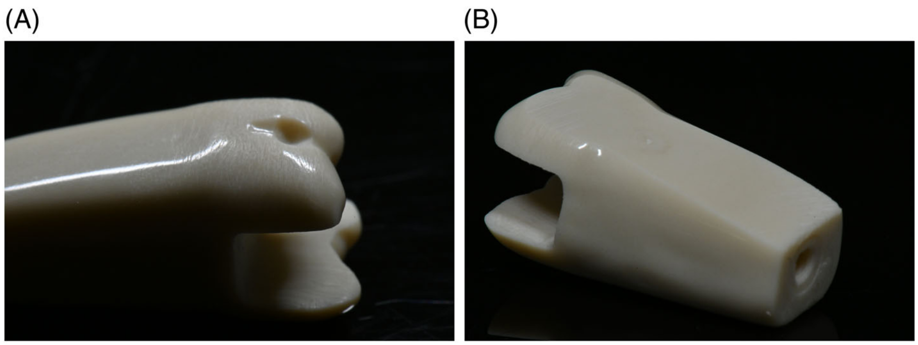

FIGURE 1 Standard MOD tooth preparation 5-mm in bucco-palatal width, 5-mm in depth, (A) buccal view with modified buccal fossa, (B) lingual view with flattened cusp and root.

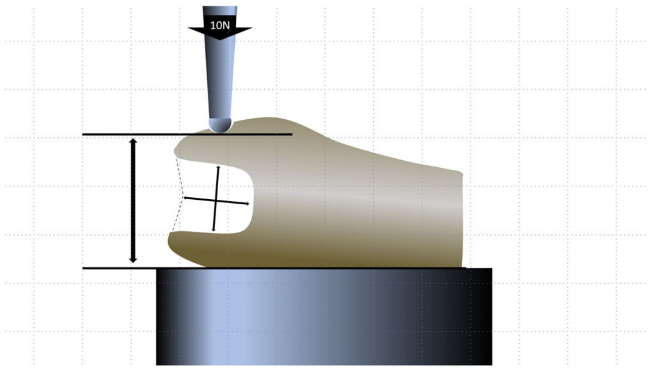

FIGURE 2 Schematic view of specimen laid flat for intercuspal distance measurement in Acumen 3 system (MTS).

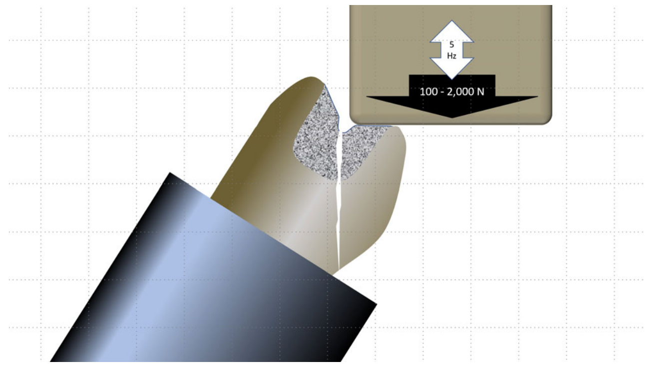

FIGURE 3 Schematic view of specimen positioned at 30° for cyclic loading in Acumen 3 system (MTS).

2.1 | Tooth preparation

A high-speed electric handpiece and tapered diamond bur (ref 6856–027, Brasseler, Savannah, GA) were utilized to prepare a standard MOD slot-type defect with a 5-mm bucco-palatal width and 5-mm occlusal depth under a microscope (Leica MZ 125, Leica Microsystems, Wetzlar, Germany). A round diamond bur (801–010, Brasseler) was used to prep 1 mm-deep fossa on the buccal cusp, centered on the buccal developmental groove (Figure 1A). A model trimmer (Ray Foster 10" Model Trimmer, USA) was used to flatten the lingual surface of the crown and root (Figure 1B) in order to facilitate intercuspal distance measurements.

2.2 | Initial intercuspal measurement

Each prepared specimen was placed on a flat stainless-steel base on their flattened lingual surface inside the test system (Acumen 3, MTS Eden Prairie MN). The contour of the root was drawn on the surface of the base with a pen to guide and repeat the precise positioning at each measurement. A 10 N load was applied to the buccal fossa (at roughly 90° angle from the tooth axis) through a spherical stainless-steel tip (1.5-mm curvature radius) (Figure 2). A total of three measurements were recorded and averaged to determine the exact intercuspal distance before restoration.

2.3 | Restoration

The prepared MOD surface of each specimen was carefully air-abraded (RONDOflex plus 360; KaVo Dental, Charlotte, NC, USA) using 30-μm silica-modified aluminum oxide (Rocatec Soft; 3M-ESPE, St. Paul, MN, USA) for 15 s at a distance of 10 mm with a pressure of 30 psi, followed by the application of 1 coat of adhesive resin (Optibond FL, bottle 2; Kerr, Orange CA). EverX restorative material was then used to bulk-fill the entire defect and was polymerized for a total of 60 s (3 × 20 s) at 1,000 mW/cm^2 (VALO Curing Light, Ultradent Products, Inc., South Jordan, UT, USA). The margins were mechanically polished (Diacomp Featherlite, Brasseler). Occlusal anatomy was modified by creating a 1 mm-deep mesio-distal groove at 90° angle to the occlusal surface (round fine diamond 801–010 bur) for all three groups to induce failure at a predictable location (Figure 3).

2.4 | Repeated intercuspal measurements

Restored specimens were kept at ambient temperature and the intercuspal distance was measured again immediately after restoration, and at 3, 18, and 24 h. Each measurement was repeated three times. The difference between the baseline position (initial measurement after preparation) and subsequent measurement at 3/18/24 h was calculated.

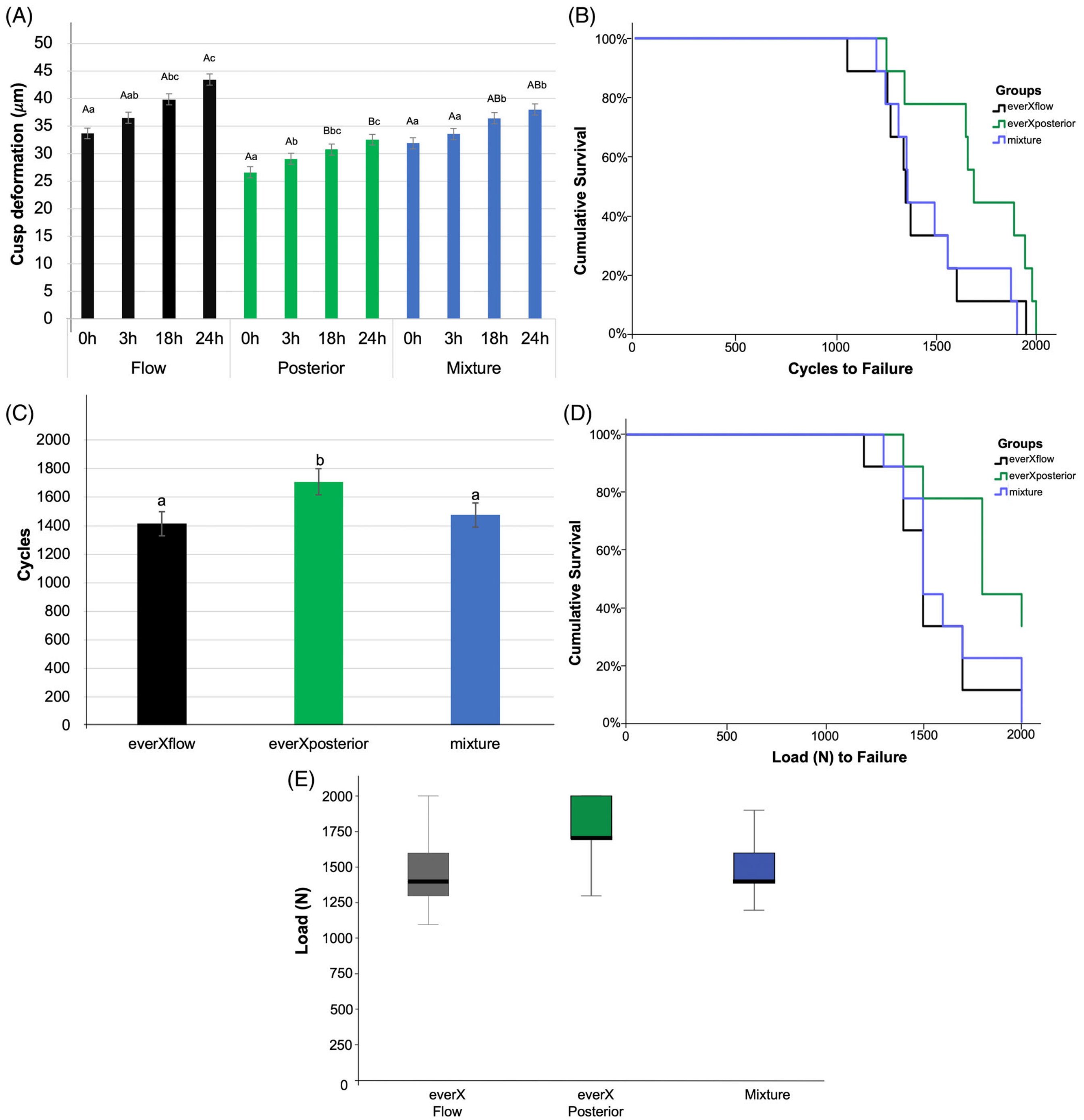

FIGURE 4 (A) Mean cusp deformation (µm ± SE) of the three experimental groups for the four different times. Different capital or small letter indicates statistically significant difference within the same time and within the same composite, respectively. (B) Kaplan–Meier fatigue resistance survival curves for cycles of all three groups. (C) Mean survived cycles and standard errors of cycles to failure. Kaplan–Meier and Log Rank post hoc test (p < 0.05) with different letters indicating significant differences. (D) Life table survival curves for load of all groups. (E) Box-and-whisker diagram of load at failure (in Newtons) presenting median (bold black horizontal line), minimum and maximum values (whiskers), total number of specimens ($N = 27$, $n = 9$), and interquartile range (box).

2.5 | Accelerated fatigue test

Once intercuspal assessments completed, specimens were mounted in a stainless-steel positioning jig 3 mm below the simulated cementoenamel junction using acrylic resin (Palapress vario; Heraeus Kulzer, Armonk, NY, USA). The test was carried in an artificial masticatory machine using a closed-loop electrodynamic system (Acumen 3). The masticatory test was simulated through a flat composite resin CAD/CAM antagonist (Lava Ultimate; 3M-ESPE-CEREC) contacting the whole buccal cusp slope (30° angle to the tooth axis). The cusp

TABLE 1 Mean cusp deformation (μm ± SE) for the three experimental groups at the four different times

	Time			
Material	0 h	3 h	18 h	24 h
everX Flow	33.7 ± 2.3^{Aa}	36.5 ± 2.9^{Aab}	39.8 ± 2.8^{Abc}	43.4 ± 2.5^{Ac}
everX Posterior	26.6 ± 1.1^{Aa}	29.0 ± 1.2^{Ab}	30.7 ± 1.5^{Bbc}	32.5 ± 1.5^{Bc}
50/50 mixture	31.9 ± 2.3^{Aa}	33.5 ± 1.9^{Aa}	36.4 ± 2.4^{ABb}	38.0 ± 2.4^{ABb}

Note: Two-way repeated measures ANOVA followed by Bonferroni adjustment for multiple pairwise comparison. Different superscript capital or small letter indicates statistically significant difference in the columns and rows, respectively.

slope was finished perfectly flat using sandpaper (1500-grit) while gently loading with the antagonist. Isometric contraction forces (load control) were applied. The cyclic load was applied at a frequency of 5 Hz, starting with a load of 100 N, which increased by 100 N every 100 cycles until 2,000 N. All load tests were uninterruptedly recorded and monitored using a macro video camera (Canon Vixia HF S100, Canon USA, Melville, NY). Samples were cyclically loaded until fracture and the number of endured cycles and failure modes of each specimen was recorded. After the test, each sample was photographed and evaluated (two-examiner agreement).

2.6 | Statistical analysis

The Shapiro–Wilk test was used to assess the normal distribution of the data ($p > 0.05$) and a visual inspection of their histogram, normal Q–Q plots, and box plots showed that the data were approximately normally distributed. Levene's test showed homogeneity of variance ($p = 0.115$). As the cusp deformation data (μm) presented sphericity (Mauchly's test, $p > 0.05$). Groups were compared using two-way repeated measures ANOVA followed by Bonferroni adjustment for multiple pairwise comparisons as a post hoc test ($p < 0.05$).

The Kaplan–Meier test was applied to compare the fatigue resistance of the groups regarding the cycles (continuous variable). The effect of the type of fiber-reinforced composite material was assessed by the post hoc log-rank test. Life table analysis was applied to compare the fracture load step at which the specimen failed (ordinal variable), followed by the Wilcoxon test for pairwise comparison. For all statistical analyses, the level of significance was set at 95%. The data were analyzed with statistical software (SPSS 23, SPSS Inc, Chicago, IL).

3 | RESULTS

3.1 | Cusp deformation

Two-way repeated measures ANOVA showed the effect of resin [$F(1.59\ 12.75) = 5.45$; $p = 0.025$] as well as the effect of the time [$F(2.08\ 16.65) = 32.614$; $p < 0.001$], but the effect of the combination of resin and time was not found [$F(2.26\ 18.07) = 0.873$; $p = 0.447$].

TABLE 2 Pairwise post hoc comparison for cycles and load

	everX Flow	everX Posterior	50/50 mixture
everXflow	–	*0.039	0.990
everXposterior	**0.035*	–	*0.047
mixture	*0.651*	*0.067*	–

Note: Nonitalic cells = Kaplan–Meier followed by post hoc Log Rank tests for cycles; Italic cells = Life table followed by post hoc Wilcoxon–Gehan test for load.
*indicates statistically significant difference between groups ($p < 0.05$).

The means and standard errors of all groups are presented in Figure 4 and Table 1.

At 0 and 3 h, no differences were found among the three composite resins. For 18 h, everX Posterior presented the smallest cusp deformation (30.7 ± 1.5 SE μm) compared with everX Flow (39.8 ± 2.8 SE μm) ($p = 0.029$) but not different from the 50/50 mixture (36.4 ± 2.4 SE μm, $p = 0.199$). Similarly, for 24 h, everX Posterior presented the smallest cusp deformation (32.5 ± 1.5 SE μm) compared with everX Flow (43.4 ± 2.5 SE μm) ($p = 0.029$) but not different from the 50/50 mixture (38.0 ± 2.4 SE μm, $p = 0.173$). Within the same composite resin, 0 h presented smaller cusp deformation than 18 and 24 h for all three composite resins ($p < 0.05$).

3.2 | Fatigue resistance

All specimens failed before the end of the test, hence the mean cycles and median load at failure could be calculated. The fatigue resistance survival curves are presented for all 27 specimens considering cycles (Figure 4B,C) and load (Figure 4D,E). The Kaplan–Meier and post hoc log-rank test for the number of cycles to failure revealed significantly higher mean ± standard error survival for the group everX Posterior (1,707.8 ± 90.6) than group Mixture (1,475 ± 85.7, $p = 0.047$) and then group everX Flow (1,414.4 ± 85.3, $p = 0.039$). No difference was found between everX Flow and the mixture group for either cycles or load (Table 2). The life table followed by the post hoc Wilcoxon test for the mean load at failure revealed significantly higher loads for everX Posterior (1,783 N) than for everX Flow (1,450 N) ($p = 0.035$). The load descriptive statistics of the data are shown in a box and whisker diagram in Figure 4E. Group everX Posterior

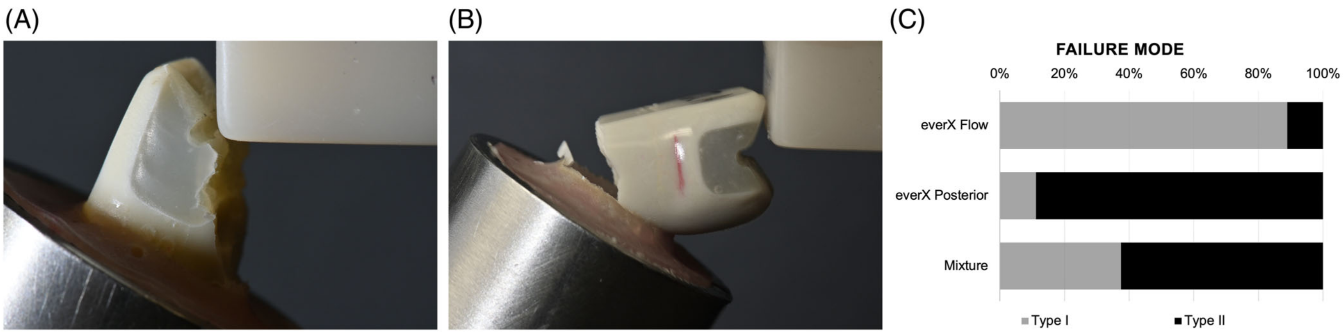

FIGURE 5 Failure modes (A, type I restorable, B, type II non restorable) and distribution for each group (C).

TABLE 3 Failure types, numbers, and percentages after the fatigue-to-failure test

Group	Type I	Type II
EverX Flow ($n = 9$)	8 (89%)	1 (11%)
EverX Posterior ($n = 9$)	1 (11%)	8 (89%)
Mixture 50/50 ($n = 9$)	4 (44%)	5 (56%)

Abbreviations: Type I, partial cusp fracture, cusp only, re-restorable; Type II, total crown fracture, root, nonrestorable.

presented more type II failure and everX Flow presented more type I failure, as shown in Figure 5.

The failure mode was evaluated to classify the fracture as restorable, or nonrestorable. Nonrestorable failure meaning total crown fracture (below the acrylic resin base limit) affected 89% of everX Posterior group, 56% the 50/50 mixture, and 11% of everX Flow SFRC (Table 3).

4 | DISCUSSION

This research assessed the strength and shrinkage-induced cuspal deformation of MOD direct restoration of molars using three different SFRC resins. The null hypotheses are rejected because (1) a significant difference in mechanical performance and failure mode among the three materials was found, and (2) cusp deformation (induced by shrinkage stress) was not the same across groups.

The goal of this in vitro study was to obtain the highest level of standardization for all procedures by controlling the nature and the dimension of substrate, preparation dimensions and restorative steps, as well as loading configuration and occlusal morphology. While using natural teeth would at first seems more realistic, plastic teeth were chosen instead to focus on the behavior of the restorative material itself. Unlike natural teeth, plastic teeth come from a single industrial mold and have identical, morphology and cuspal deformation properties.

The standardization level achieved here would never be possible in a clinical study due to the number of confounding variables, such as the patients' dietary habits, caries susceptibility, masticatory factors, tooth morphology, variability in hard tissue properties and dimensions, and so forth.

One of the most challenging factors in conducting a true fatigue test is the complexity of the process, testing at low load/high cycles is time-consuming as it involves performing over 1,000,000 cycles before a failure can be observed. The accelerated fatigue test introduced by Fennis et al.,[29] which is performed in a relatively short time, is the most relevant assessment method. The Acumen 3 (MTS) electrodynamic system used in this study features a rigid load frame, micron-accurate displacement sensors and an automatic linear motor that can provide highly precise motion and load control.

The angle of force was modified to 30° and applied to the supporting cusp using a composite resin CAD/CAM block (Lava Ultimate; 3M-ESPE-CEREC) as an antagonistic cusp. This measure escalated the stress to the restoration and replicate an extreme load scenario (non-working contact). The specimens were subjected to extremely high loads, which were used far beyond the physiological limits of masticatory forces, all specimens survived the first half of the experiment (>1,000 N), demonstrating outstanding survival rates. Due to standardization, fracture modes were consistent (type I or type II).

everX Posterior (GC) is a unique bulk-fill dentin-replacement hybrid composite resin containing E-glass fibers of 1–2 mm length. Other FRC materials (Alert by Generic Pentron and Restolux by Lee Pharmaceuticals) preceded everX by more than a decade and were offered as condensable composite resins with increased fracture toughness. The glass fibers, however, were chopped to a very short size (60–120 microns length) and mechanical properties were only slightly better than those of most conventional composites with traditional fillers. Fiber fillers require a critical fiber length (in the millimeter scale) in order to significantly influence overall mechanical properties. This was the goal of everX Posterior, which is recommended for high stress-bearing areas. It presents a high fracture toughness (2.6 MPa $m^{1/2}$) and flexural modulus within the family of bulk-fill materials but can be used easily in 4-mm deep increments and can potentially match the toughness of dentin. Alike most FRC materials, it cannot be polished well and can only be used as an internal build-up or base to be covered with a regular composite resin (microhybrid or nanohybrid). In the present study, however, it was decided not to introduce this confounding variable and use only the SFRC, which in turn allowed to reveal the discrepancy between the different formulations. everX Posterior proved to be worth of consideration when restoring large defects that would normally require a semi-direct or indirect approach, but for which a direct technique is the only

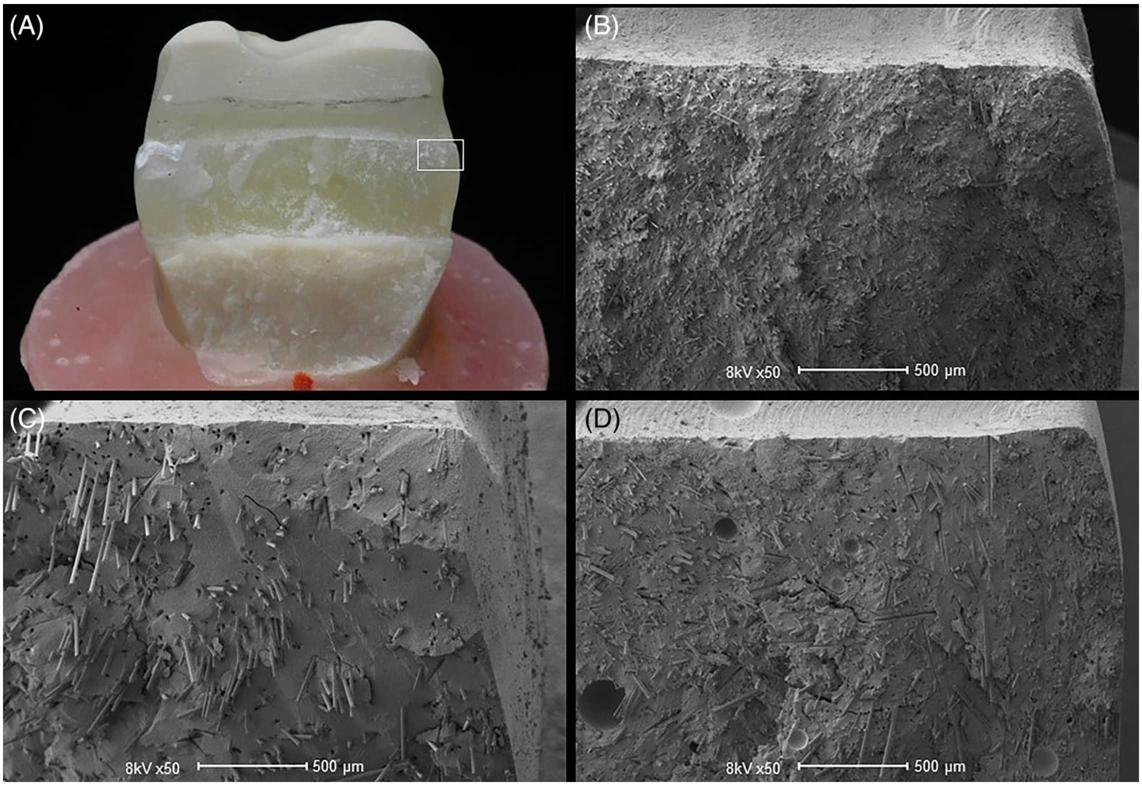

FIGURE 6 Fractured specimens of the three groups. (A) Macrophotography of a sample, showing the area (white rectangle) used for the scanning electron microscopy images (SEM) of the groups. (B) SEM of everX Flow sample presenting a higher density of smaller fibers. (C) SEM of everX Posterior sample presenting lesser density of fibers with greater dimensions. (D) SEM of 50/50 mixture sample presenting both types of fibers (hybrid composition) and voids incorporated during the mixture process.

option due to financial and patient limitations. As such, it was able to match the performance of CAD/CAM semidirect composite resin inlays.[20] everX Posterior could be regarded as a possible substitute of the GIC in the sandwich approach, provided that it is covered with a sufficiently bright material to compensate for its excessive translucency. The present study does align with existing data about the shrinkage difference between the two SFRC.[22] The flowable SFRC was obtained by reducing the barium glass filler content and modifying the resin matrix, in addition to decreasing the critical fiber length. It seems that the resulting increase in fiber content (Figure 6) was not enough to make up for the lost volume, possibly explaining the increased shrinkage rate in EverX Flow. The present results, however, does not support the existing data about the superior fracture toughness of everX Flow[21,22] because everX posterior had superior fracture resistance. The lower flexural modulus (9.0 GPa) of everX Flow along with the reduced fiber length (below the critical level) might explain this difference.

In view of the above and considering clinical feasibility, it seems advisable that everX Posterior be recommended in large direct restorations (easy to apply in large bulk) while everX Flow can be used rather as a liner (small volume) on top of immediate dentin sealing to smoothen the geometry and protect the dentin bond when doing semi-(in)direct CAD/CAM restorations.

Alike the mixture of microfiller and macrofiller in hybrid composite resins, the 50/50 mixture presented with the potential to generate synergetical properties. However, the mixture only revealed intermediate performances between the Flow and Posterior versions of the material for both cuspal deformation and strength. This absence of synergy might have been caused by the significant number of voids incorporated during the mixing process (Figure 6D).

Increased cuspal deformation will logically increase the risk of cracking in enamel. Totally avoiding this problem is only possible with inlays. In direct techniques, the very limited incidence of cracks speaks for EverX Posterior performance in another study.[20]

It is the essence of Biomimetic Restorative Dentistry (BRD) to mimic tooth structure and as such, SFRCs constitute the most biomimetic dentin replacements because of their superior fracture toughness. Natural dentin is reinforced by collagen fibers that can stop and deflect cracks initiated from enamel. A significant outcome of this experiment is the combination of lesser cuspal deformation induced by shrinkage and higher strength for the direct restorations with everX Posterior SFRC base. These outstanding properties, however, made the crown so strong that failure was directed toward the root. Large MOD defects have proven best to be restored using CAD/CAM inlays with an SFRC as a base for optimal strength with lower shrinkage-induced cracks, and most friendly failure modes.[20] When a low-cost restoration must be chosen instead, the SFRC alone will significantly improve the performance of direct restorations.

5 | CONCLUSIONS

This study assessed the shrinkage-induced cuspal deformation and strength of large MOD restorations using three different SFRC resins (everX Posterior, everX Flow, and mixture 50/50). Restorations with everX Posterior SFRC yielded excellent mechanical performance with the least amount of shrinkage-induced cuspal deformation and the higher average strength. everX Flow tended to demonstrate more repairable partial fractures while the extreme strength of EverX Posterior induced mainly catastrophic failures.

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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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