Short Fiber Based Filling Composites

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7.1 Introduction

Direct conventional resin composite restorations, i.e., particulate filler resin composite (PFC) restorations are a routine approach of treating lost tooth structure conservatively. Beside the ability to bond to hard tooth tissues, mediated by adhesive systems, they feature the advantage of natural shade and are less expensive compared with cast gold and ceramic indirect restorations [1]. The use of resin composites has increased tremendously during the last two decades. Today, resin composites are selected on a regular basis for direct (bulk fill or layered) and laboratory made posterior restorations, as an extension to their original indication, which was limited to direct restorations in anterior teeth. Their use has been widened not only to the posterior intra-coronal area, but also to extra-coronal restorations [2]. In addition, resin composites are used for the fabrication of resin-bonded fixed dental prostheses (RBFDP) following the introduction of fiber-reinforced composites (FRC). However, inadequate material properties limited the success of resin composite restorations in high stress-bearing areas [3, 4]. Resin composites were introduced to the dental community in the 1960s [5]. Since then, significant material improvements have been introduced. However, resin composite still suffers from a lack of mechanical properties and polymerization shrinkage. Resin composite restorations have shown good overall clinical performance in small and medium sized posterior

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restorations with annual failure rates between 1% and 3% [3, 6]. Secondary caries and fracture are among the most important reasons for clinical failure [6, 7]. Survival of posterior restorations strongly correlates with the size of the restorations. Bernardo et al. reported an increase in annual failure rate from 0.95% for single-surface restorations to 9.43% for four or more surface restorations [8]. Large restorations were more prone to fracture-related failures resulting in decreased longevity [9, 10]. The higher susceptibility of large resin composite restorations to fracture may be related to the use of glass-ionomer lining material, strength-related properties of the resin composite material itself and patient factors such as bruxism [6, 11]. Besides restoration size the endodontic status of a tooth strongly affects the longevity of resin composite restorations. Clinical studies revealed a decreased longevity for resin composite restorations in endodontically treated teeth, with an increased annual failure rate of 2–12.4% when compared to vital teeth [6, 12]. Furthermore, non-vital teeth are susceptible to unfavorable subgingival cusp fractures [13]. The above-mentioned reasons make the restoration of endodontically treated teeth a true challenge.

It is clear from the literature that contemporary resin composites still demonstrate limitations due to their insufficient mechanical properties when used in large restorations. Due to failures of this kind, it is still controversial, whether restorative resin composites should be used in large high stress-bearing applications such as in direct posterior restorations or core build-ups [3, 14]. The relatively high brittleness and low fracture toughness of current PFCs still hinder their use in these large stress-bearing restorations [15, 16]. Appropriate physical and mechanical properties and satisfactory esthetic are all characteristics that restorative resin composite should achieve.

7.2 Biomimetic Dentistry

Contemporary restorative dentistry uses direct, semi-direct as well as indirect restorations to restore lost tooth tissue with biomimetics as the new driving force. Biomimetic dentistry tries to mimic nature by studying the structure, function and biology of the tooth organ as a model for the design and engineering of new or improved materials and techniques to restore or replace teeth in biomechanically optimal way [17]. From a biomimetic point of view, we strive to replace lost tooth tissue by biomaterials with similar physical properties, especially with reference to fracture toughness, elastic modulus, strength, and thermal expansion coefficient [18, 19]. A well accepted biomimetic restorative approach advocates replacing enamel with feldspathic porcelain or glass ceramic and dentine by conventional PFCs [19, 20]. Although such approach seems effective, there are still relevant mechanical properties, such as fracture toughness, not considered. Fracture toughness of PFC is still lower than that of dentine [1]. Furthermore, the microstructure of PFC does not resemble that of dentine. PFC consists of filler particles embedded in a resin matrix while dentine consists of collagen fibers embedded in a hydroxyapatite matrix. Therefore, dentine should be rather seen as a fiber-reinforced composite. Collagen fibers act as crack stopper and gives dentine unique properties by making it resilient, flexible and tough at the same time. For that reason, improvement might be found when taking advantage of a more dentine-like and high toughness resin composite as dentine replacement.

Extensive research has been conducted to improve the reinforcing phase of restorative PFC in order to increase their suitability for use in high stress-bearing areas. Attempts have been made to change the type of filler or the filler size and their silanization [21–26]. Reinforcing the resin composite with short glass fibers has been one of the most effective approaches among the methods that have been studied [23, 27, 28]. Short fibers enhanced the ability of the material to resist the crack propagation, as well as to reduce the stress intensity at the crack tip from which a crack propagates in an unstable manner. As a consequence, an increased resin composite toughness should be expected. A number of manufacturers have developed short fiber-reinforced composites (SFRCs) which claimed to overcome the weakness of conventional PFC (Table 7.1). However, comparative studies from the literature showed that commercial SFRCs have different properties, structures, and reinforcing capacities [29, 30]. Recent studies showed that millimeter and micrometer scales SFRCs (everX Posterior and everX Flow; GC Corporation) had a significant superior fracture toughness and reinforcing capability when compared to other commercial SFRCs (Alert, NovaPro-Flow, NovaPro-Fill, EasyCore, Build-It and TI-Core) [29, 30]. Based on this, everX

Table 7.1 Short fiber-reinforced composites

Brand	Type	Composition
everX Posterior (GC Corp, Tokyo, Japan)	LC Packable	Bis-GMA, PMMA, TEGDMA, millimeter scale glass fiber filler, barium glass 76 wt%, 57 vol%
everX Flow (GC Corp, Tokyo, Japan)	LC Flowable	Bis-EMA, TEGDMA, UDMA, micrometer scale glass fiber filler, barium glass 70 wt%, 46 vol%
Alert (Jeneric/Pentron, Wallingford, CT, USA)	LC Packable	Bis-GMA, UDMA, TEGDMA, THFMA, silica and micrometer scale glass fiber 84 wt%, 62 vol%
NovaPro Flow (Nanova, Columbia, MO, USA)	LC Flowable	Bis-EMA, UDMA, TEGDMA, Barium silicate, amorphous fumed silica, nanometer scale hydroxyapatite fiber (% NA)
NovaPro Fill (Nanova)	LC Packable	Bis-EMA, UDMA, TEGDMA, Barium silicate, amorphous fumed silica, nanometer scale hydroxyapatite fiber (% NA)
EasyCore (SpofaDental, Markova, Czech Republic)	DC Flowable	Bis-GMA, HDMA, glass fiber
Build-It (Jeneric/Pentron)	DC Flowable	Bis-GMA, UDMA, HDMA, 67.3 wt% Boroaluminosilicate glass and chopped glass fiber
TI-Core (Essential Dental Systems, Hackensack, NJ, USA)	AC Packable	Bis-GMA, titanium and lanthanide reinforced 75 wt%

Bis-GMA bisphenol-A-glycidyl dimethacrylate, *UDMA* urethane dimethacrylate, *TEGDMA* triethylene glycol dimethacrylate, *Bis-EMA* ethoxylated bisphenol-A-dimethacrylate, *THFMA* tetrahydrofurfuryl-2-methacrylate, *PMMA* polymethylmethacrylate, *HDMA* hexanediol dimethacrylate, *LC* light cured, *DC* dual cured, *AC* auto cured, *wt%*, weight percentage, *vol%* volume percentage, *NA* not available

Posterior and everX Flow are the most interesting dentine-replacing materials because of their close resemblance to dentine at the level of microstructure and mechanical properties [18, 31, 32].

7.3 Structure and Properties

Many of the properties of SFRCs are strongly dependent on microstructural parameters such as fiber diameter, fiber length, fiber orientation, fiber loading, and adhesion of fibers to the polymer matrix [33]. For a fiber to act as an effective reinforcement for polymers, stress transfer from the polymer matrix to the fibers is essential [33]. This is achieved by having a fiber length equal to or greater than the critical fiber length and the given fiber aspect ratio in the range of 30–94 [33–35]. Aspect ratio, critical fiber length, and fiber loading are the main factors that could improve or impair the mechanical properties of SFRCs. Aspect ratio is the fiber length to fiber diameter ratio (l/d). It affects the tensile strength and the reinforcing efficiency of the fiber-reinforced material [33]. It should be noted that adhesion of the fibers to the polymer matrix also influences to the critical fiber length. Sufficient adhesion between fiber and matrix provides good load transfer between the two components, which ensures that the load is transferred to the stronger fiber, and this is how the fiber actually works as reinforcement. However, if the adhesion is not strong and if any voids appear between the fiber and the polymer matrix, these voids may act as initial fracture sites in the matrix and facilitate the breakdown of the material [36].

For instance, Alert has fiber length in micrometer scale (20–60 μm) and diameter of 7 μm (Fig. 7.1), while NovaPro composites have fiber diameter in nanometer scale (50–200 nm) and length in range between 100 and 150 μm, which is well below the critical fiber length and desired aspect ratio [30]. This explained the difference in fracture toughness values between the commercial SFRCs. These differences were seen by SEM analysis (Figs. 7.1 and 7.3), which prove that materials

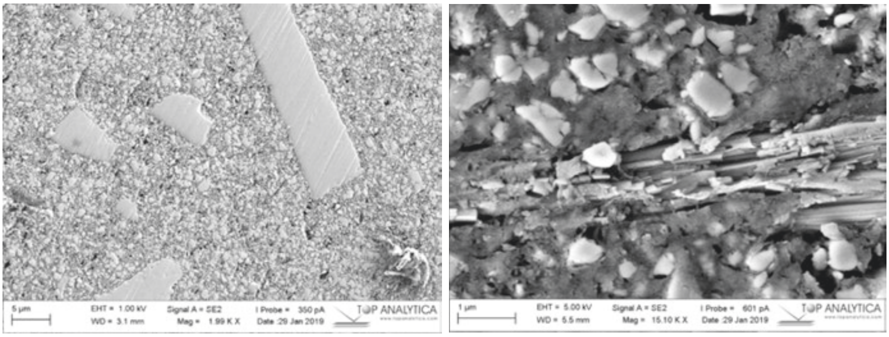

Fig. 7.1 SEM photomicrographs of polished surface of SFRCs showing the micrometer scale fiber in Alert (left side) and nanofiber bundle in the NovaPro Flow (right side)

with different microstructure characteristic and fiber aspect ratio (length and diameter) could differ with regards to physical properties and toughness.

Earlier formulations of SFRC showed a high failure rate due to secondary caries and bulk fracture [37, 38]. Bulk fracture of earlier SFRC formulations was related to sub-optimal reinforcement of the polymer matrix by short fibers. These SFRCs did not fulfill the reinforcing requirements. Aspect ratio and critical fiber length have implications towards fracture toughness (K_{Ic}), a property of major influence on the clinical performance of a material [39]. Fracture toughness of earlier SFRC formulations is much lower than that of dentine [1].

Following this knowledge, a millimeter scales packable SFRC (everX Posterior) was launched in 2013. It consists of a combination of a resin matrix (24 wt%), randomly orientated E-glass fiber (9 wt%) and inorganic particulate fillers (67 wt%) [27, 34]. The resin matrix comprises cross-linked monomers bis-GMA and TEGDMA accompanied with linear PMMA. This combination of resins enables the formation of the semi interpenetrating polymer network (semi-IPN) during the polymerization of the material, which provides good bonding properties and improved toughness of the resin composite [36]. The short, randomly oriented fiber on the other hand, provide an isotropic reinforcing effect when placed in bulk, which means that the strength of the material is independent of the fracture load direction, i.e., it is the same in all directions. Nevertheless, in the origin isotropic SFRC material (3D fiber orientation and fiber reinforcing factor of 0.2) becomes anisotropic and subsequently more biomimetic when applied in incremental layers up to 2 mm thick, due to alignment of fibers in the plane of application (2D fiber orientation and fiber reinforcement factor of 0.38) [33].

In 2019, the flowable version of SFRC (everX Flow) was introduced with the promise of easy handling and better adaptability in limited spaces. It consists of a combination of a resin matrix (30 wt%), randomly orientated glass microfibers (25 wt%) and inorganic silanated particulate fillers (45 wt%) (Fig. 7.2) [40, 41].

The micrometer scale SFRC (everX Flow) had an aspect ratio of more than 30 because the diameter of microglass fibers used was 6 μm and the length in the range

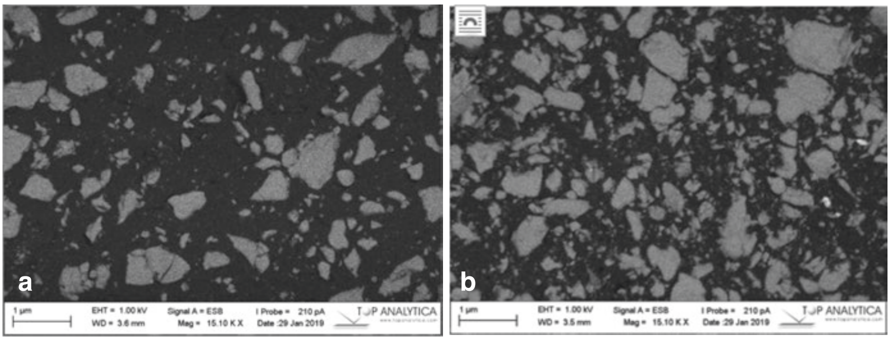

Fig. 7.2 SEM photomicrographs of polished surface of SFRCs (scale bar = 1 μm) showing different filler weight percentages. (**a**) everX Posterior; (**b**) everX Flow

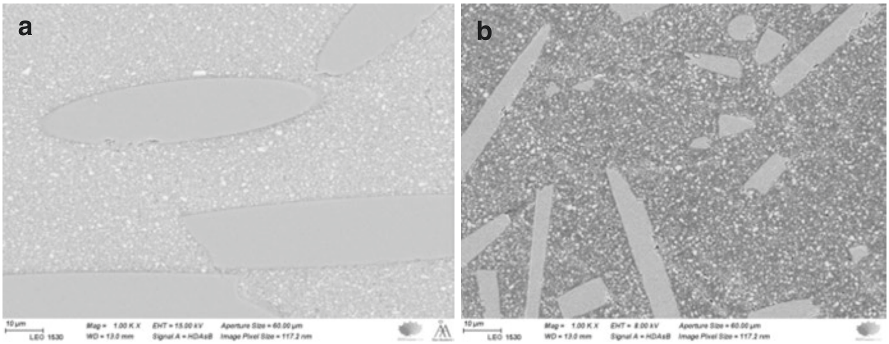

Fig. 7.3 SEM photomicrographs of polished surface of SFRCs (scale bar = 10 μm) showing different fiber diameters. (**a**) everX Posterior; (**b**) everX Flow

of 200–300 μm. everX Posterior had fiber (Ø17 μm) length distribution between 0.3 and 1.5 mm, which is in the range of the reported critical fiber length and desired aspect ratio (Fig. 7.3). It is therefore not surprising that everX Posterior and everX Flow have superior fracture toughness in comparison to all other commercial fiber filled resin composite.

These SFRCs were reported to exhibit improved mechanical properties regarding strength, fracture toughness, fatigue resistance, and polymerization shrinkage and to show a more favorable (repairable) type of failure behavior in comparison to PFCs [27, 28, 35, 40, 42–45]. The use of fiber fillers with a length in the range of the reported critical fiber length and desired aspect ratio, increased K_{Ic} of SFRCs up to 2.6–3.1 MPa $m^{0.5}$ [35, 40, 46, 47] in comparison to 1.2–1.8 MPa $m^{0.5}$ of conventional PFC [48]. Therefore, it can be hypothesized that the replacement of dentine by a high toughness SFRCs can reduce bulk fractures and therefore increase longevity of large resin composite restorations.

There is little evidence comparing bond durability of SFRC to dentine with that of other conventional PFCs [49, 50]. A study by Tsujimoto et al. determined that the relationship between mechanical properties and dentine bond durability of SFRC using universal adhesives showed improvements compared to conventional PFCs [49]. Regardless of adhesive type and etching modes, the ratios of shear fatigue strength and shear bond strength of SFRC were higher than those of conventional PFCs. The authors clarified that superior mechanical properties of SFRC, especially fracture toughness, could improve its bond durability with universal adhesives [49, 50]. Studies have debated if short fibers might have a reinforcing effect on the oxygen-inhibited layer of the adhesive and they emphasized that, with enhanced mechanical properties and bond durability, SFRC might perform better in high stress-bearing situations.

Curiously, SFRCs have the ability to conduct and scatter the curing light better than conventional PFCs and thus it is suitable for use in bulk of 4–5 mm layer thickness [40, 51, 52]. Surface roughness, wear and esthetic related limitations of SFRCs can be overcome by adopting a biomimetic restorative approach, in which dentine is replaced by SFRC and covered by a more wear-resistant PFC [1, 18]. Such

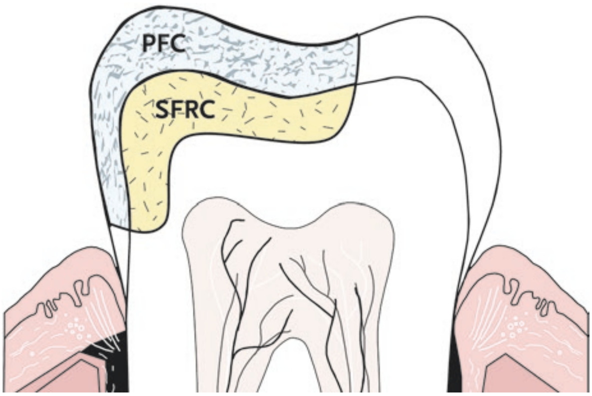

Fig. 7.4 Schematic representation of a direct biomimetic restoration: lost dentine is replaced by high toughness SFRC and covered by a wear-resistant enamel-replacing PFC

approach not only has the benefits of better wear resistance but also increased strength and fatigue resistance. SFRCs are suitable as a bulk base or core foundation and should not be used as final restoration. Although, microfibers filler loading was not seen to be worsening the wear or the gloss of the flowable SFRC (everX Flow) [40, 53]. Clinically, it is widely recommended nowadays to use a layer of composite bulk base (dentine replacing) material in order to improve the esthetic, to reduce the polymerization stress and to develop better mechanical properties [54]. The latter is accomplished by decreasing the tensile stress concentrations at the restoration interface and reducing the cuspal strain [54]. Published clinical results of bilayered restorations (Fig. 7.4) containing SFRC as bulk composite base in high stress-bearing areas have shown good clinical performance. However, the time frame and case numbers for these clinical trials were not of such duration and number as to indicate the long-term suitability of the tested restorations [55–57].

7.4 Benefits of Using SFRCs as Bulk

Bilayered composite structure of SFRC as substructure and PFC as top surface layer (Fig. 7.4) has been evaluated in several in vitro investigations and with different applications [58–63]. SFRC base has already been used to reinforce large direct composites restorations in vital teeth [64–68] as well as in endodontically treated teeth [69–73], as prosthesis infrastructure [74–78], onlay restorations [59, 79], and endodontic post/core foundations [70–73].

The effect of the thickness of the SFRC substructure versus the thickness of the overlaying PFC, static and fatigue load-bearing capacity of materials combination and the interface between SFRC and PFC are among the issues that have been studied [21, 22, 80, 81].

These studies demonstrate that SFRC substructure supports the PFC layer and serve as a crack preventative layer. SFRC substructure's thickness is important, as it influences the failure mode and the crack arresting mechanism. The mechanism of arresting the crack propagation is greatly influenced by the distance between the SFRC substructure and the surface where the stress initiates. The applied SFRC and

PFC layers thickness is extremely important. The ratio between the SFRC base and surface PFC should be an analogue to the dentine and enamel structure. In vitro it was observed that optimal thickness of the veneering PFC composite over the SFRC substructure is around 1 mm [21, 22, 80]. It is important to point out that less benefit is achieved if the layer of SFRC is not sufficiently thick [77, 81]. Other advantages of SFRC-based biomimetic restorations can be seen at the level of the interface between SFRC and PFC [82, 83]. After application of the SFRC layer some fibers are protruding from the surface which can be embedded in the veneering PFC layer and form an interface similar to that found at the dentine-enamel junction (DEJ). At the DEJ, collagen fiber originating from dentine extends into enamel creating a fiber-reinforced connection between enamel and dentine. It is known that the microscopic architecture and the unique mechanical properties of the DEJ acts as a natural crack arrest barrier [84].

Theoretically, the significant advantage of this bilayered or biomimetic restoration is their ability to mimic the natural behavior of enamel and dentine. To the author's knowledge, these SFRCs are the only available resin composites that mimics structurally the dentine at this time.

7.5 Clinical Use of SFRCs

In this series of clinical cases an attempt was made by using SFRCs as bulk base or core material under surface layer of conventional PFC, i.e., direct biomimetic or bilayered composite restorations, in order to improve the load-bearing capacity and clinical longevity of resin-based composite restorations.

7.5.1 Clinical Case: everX Posterior

A 49-year-old male presented with a defective Class II amalgam restoration and a primary carious lesion on a lower second premolar (FDI #45) (Fig. 7.5a). The old restoration was removed using a pear-shaped diamond bur (830 L; Komet) in a high-speed air turbine. Dental dam was placed after opening the cavity, in order to obtain a dry working field. The minimal invasive cavity was cleaned by sandblasting with 50 µm alumina particles. A three-step etch-and-rinse adhesive (Optibond FL, Kerr) was applied according to manufacturer's instructions. The resin composite was placed following an incremental filling technique and interproximal contacts were restored by use of metal sectional matrices in combination with separation rings (V3 matrix and ring, Triodent) (Fig. 7.5b). The centripetal filling technique was adopted to transform the three-surface cavity into a single-surface cavity (Fig. 7.5c): a first 1 mm thick layer of hybrid composite (Filtek Supreme XTE; 3 M ESPE) was placed towards the matrix and the subsequent layers (2 mm thick) of SFRC (everX Posterior; GC) were placed oblique (Fig. 7.5d). The biomimetic restoration was finalized by placing a final 1.5 mm thick increment of hybrid composite at the occlusal surface. Each increment of resin composite was light-cured with an LED-curing unit (The cure; Spring Health Products) for 40 s. Additional

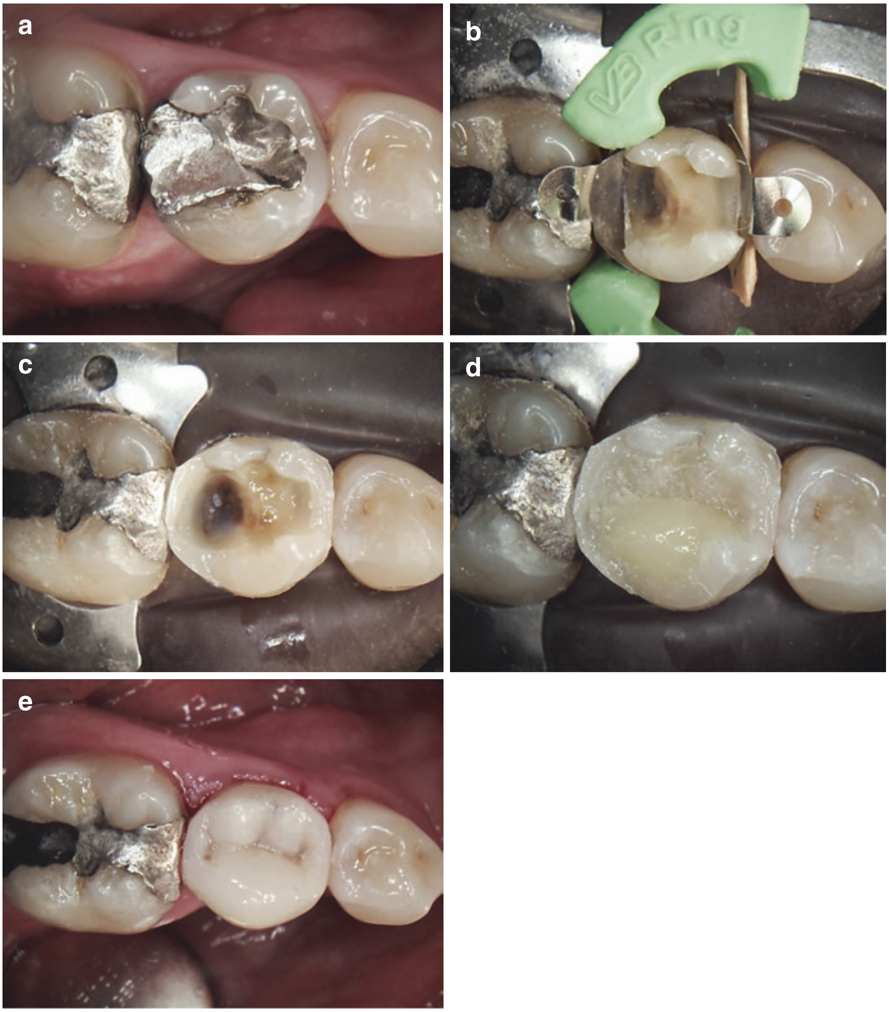

Fig. 7.5 (**a**) Pre-operative view: Clinical view of a defective amalgam restoration in combination with a primary carious lesion at the mesial wall. (**b**) After removal of the old restoration and the carious lesion a dental dam is placed and countered sectional metal matrices in combination with a separation ring. (**c**) Interproximal walls were build-up by PFC according to a centripetal filling technique. (**d**) Missing dentine replaced by a semi-IPN-based bulk short fiber composite base (notice protruding fibers from the SFRC surface). (**e**) Post-operative view: The occlusal part is build-up with hybrid composite and the restoration is finished and adjusted in occlusion

post-curing from the buccal and lingual aspect was performed after matrix removal. Occlusion and articulation were checked and adjusted after removal of the dental dam. The restoration was finished with fine-grit diamond burs (8862 and 862EF; Komet), abrasive discs (OptiDisc; KerrHawe) and strips (Sof-Lex strips; 3 M ESPE) and polished with rubbers (HiLuster; KerrHawe) and brushes (OccluBrush; KerrHawe) (Fig. 7.5e).

7.5.2 Clinical Case: everX Flow

A female patient presented with secondary caries due to a defective Class II amalgam restoration on a lower first molar (FDI #36). This case was treated according to the same principles and protocol as the previous case. The main difference between this and the previous case was the SFRC used, a flowable SFRC (everX Flow) instead of packable SFRC (everX Posterior) for replacing the lost dentine tissue (Fig. 7.6a–f).

Fig. 7.6 (**a**) Pre-operative view: Clinical view of a defective amalgam restoration and secondary caries on the lower first molar (FDI #36). (**b**) Countered sectional metal matrices in combination with a separation ring is placed in order to rebuild the distal wall, a part of the buccal cusp and the lingual cusp. (**c**) Centripetal filling technique is used to rebuild the missing distal wall and lingual cusp with several portions of enamel-replacing PFC. (**d**) A flowable SFRC (everX Flow) is applied in several increments to replace the missing dentine. (**e**, **f**) post-operative view: A nanohybrid composite is selected to restore the occlusal part of the tooth

7.6 Conclusion and Future Trends

Many clinical studies for direct and indirect large posterior composite restorations have identified that fracture of the restoration was the most common reason for failure with no significant differences between the two techniques. It is hypothesized that using SFRC substructure could reinforce the composite restoration for use in high stress-bearing areas of the dental arch. The function of the bulk SFRC base is assumed to be based on supporting the superficial conventional PFC and behaving as a crack arrest barrier. In other words, it mimics the natural behavior of enamel and dentine. The present chapter briefly described the structure, properties and benefits of using SFRC in many clinical situations. Within the limitations of this case series of clinical indications, SFRCs are a promising material that give the clinician the opportunity to replace missing tooth tissue in a more biomimetic way. Therefore, SFRCs can be beneficial in large stress-bearing restorations as a dentine-replacing materials, resulting into less fracture-related failures and improving overall longevity of direct and indirect resin composite restorations. Long-term clinical studies are currently in progress to determine the value and usefulness of using bilayered or biomimetic composite restorations made of a high toughness dentine-replacing SFRC and a wear-resistant and highly esthetic PFC as enamel-replacement in high stress-bearing areas.

Future developments in short fiber reinforcement technology are focused now on the optimization of the SFRC CAD/CAM blocks [85–87] and SFRC as 3D printing material, in order to have bilayered composite restorations. Efforts to get even closer in producing a material suitable to replace lost dentine include the investigation of using nanofibers and a compositions and structure closer to an apatite minerals in order to enhance the performance resin composite.

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