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Load-bearing capacity of novel resin-based fixed dental prosthesis materials

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To evaluate the influence of different materials on the load-bearing-capacity of inlay-retained fixed-dental-prosthesis (FDP). Ten types of FDPs were evaluated (n=7/group): Group PEEK: CAD-CAM polyetheretherketone (PEEK-TechnoMed), Group RC, made of discontinuous-fiber-composite (EverX Posterior); Group FRC1, made of discontinuous-fiber-composite (EverX Posterior) with two-bundles of continuous-unidirectional fiber-reinforced-composite (FRC) (Everstick C&B); Group FRC2, made of discontinuous-fiber-composite (EverX Posterior) with two-bundles of continuous-unidirectional-FRC (Everstick C&B) covered by two-pieces of short-unidirectional-FRC (Everstick C&B) placed perpendicular to the main-framework; Group FB, CAD-CAM fiber-block (Fibra-Composite Bio-C); Group PMMA, CAD-CAM polymethyl methacrylate block (Temp basic); Group RP, resin-paste; Group FRP1, made of resin-paste (G-Fix) with two-bundles of continuous-unidirectional-FRC (Everstick C&B); Group FRP2, made of resin-paste (G-Fix) two-bundles of continuous-unidirectional-FRC covered by two-pieces of short unidirectional-FRC placed perpendicular to the main-framework and Group exp-FRC, experimental CAD-CAM FRC. The bridges were statically-loaded until fracture. Fracture modes were visually examined. ANOVA revealed that significant differences were observed between FDP-materials (p<0.05). In addition, fiber addition to the framework significantly affected load-bearing-capacity (p<0.05).

Keywords: CAD-CAM, Fiber-reinforced-composite, Polyetheretherketone, Polymethyl methacrylate, Resin paste

INTRODUCTION

There has been an increased interest in the use of dental resin composites to restore lost dental tissues by dental treatments including extra-coronal restorations, and even complete crowns and fixed partial dentures in the posterior region[1,2]. However, under high occlusal stress, complications might occur with the composite restorations that could negatively affect the long-term clinical success of these restorations. Therefore, fiber reinforced composite (FRC) materials have been developed to improve the mechanical properties of composite resins[3]. In previous studies, these materials were reported to improve the strength of the restoration, by acting as a stress-breaker and deviating the crack propagation[2,3]. Since, these applications are metal-free, minimal invasive, cost-effective, tissue-saving and aesthetic; they might be used in patients for replacing missing single or multiple anterior or posterior teeth[3,4].

Previous *in vitro* and *in vivo* studies are available in literature regarding load-bearing capacities of inlay-retained FRC fixed-dental-prosthesis (FDPs)[5-7]. A previous study evaluated the effect of pontic materials and occlusal morphologies on the fracture resistance of FRC inlay-retained FDPs and reported that load-bearing capacity values were between 509–598 N[5]. In addition, Waki *et al.* investigated the effect of FRC in different positions on the fracture load of inlay-retained FDPs and the values were in the range of 570–943 N[7].

Recently, a new type of discontinuous FRC composite (EverX Posterior) was presented to be used in large cavities of vital and non-vital posterior teeth. Additionally, it consists of a combination of resin matrix, discontinued E-glass fibers and inorganic particulate fillers[8]. Furthermore, recent studies investigated mechanical performances of this material and reported promising performance in high load bearing areas[9,10].

Direct resin composites are the most conservative approaches for minimal sized cavities[6,11]. However, many of the problems associated with the direct placement of large posterior composite restorations can be overcome with the use of an indirect restoration such as inlays and onlays[2]. These types of restorations could be produced by a dental technician in the laboratory or by means of computer-aided design/computer-aided manufacturing (CAD/CAM) as it reduces laboratory time and material costs[12,13]. A variety of novel CAD-CAM materials such as polyetheretherketone (PEEK), FRC and polymethyl methacrylate (PMMA) are currently available as alternative materials to conventional FDP materials[1,14,15]. Although at the beginning, manufacturers introduced these polymer products for interim and long-term provisional restorations; in previous studies, composite, PEEK and PMMA-based materials were shown to have significantly improved mechanical properties[4,16]. The major advantages of these materials are reduced enamel wear in antagonists, lower costs and time exposure compared to glass-ceramics. Additionally, PMMA-based materials have lower discoloration rate and higher fracture load

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compared to composite restorations[17]. Moreover; CAD/CAM-fabricated PMMA restorations from industrially fabricated resin blocks have higher mechanical stability when compared with conventionally fabricated restorations[18].

The novel high performance composite PEEK is used in the medical field for trauma, orthopedic and spinal implants and known as the polymer from the main group of polyaryletherketone (PAEK) material. It consists of an aromatic molecular chain interconnected by ketones and ether functional groups and could be classified as a semi-crystalline thermoplastic polymer[19,20]. In dental field, there are ongoing clinical applications and research about their use in fabricating dental implants, abutments, removable partial denture frameworks, FDPs, telescopic and precision attachments as well as implant-supported suprastructures[16]. It has high biocompatibility, thermal, chemical and mechanical stability[16,20]. In addition, it offers high strength, low deformation pattern, low moisture absorption, low density, bone-like elasticity, good milling and grinding properties[1,21].

The resin paste material, G-Fix, is a flowable resin-based material, used for temporary splinting. Additionally, manufacturer claimed that the material has a polymer network with wide cross-link resulting in flexible and high toughness structure. To the authors' knowledge, no information exists in literature regarding this material. Therefore, it seemed that such a flexible composite resin might also help to relieve other stress factors, such as occlusal load, on FDPs.

To date, some studies on load bearing characteristics of the inlay-retained FDPs have been reported[4,14]. However, limited information exists in literature about load-bearing capacities of inlay-retained bridges made from different materials and their combinations. Therefore, the present study aimed to compare the load bearing capacity of different materials and their combinations. Additionally, the load bearing capacity of FRC reinforced FDPs were investigated. The tested null hypothesis was twofold. (1) The type of FDP material and their combinations would not have significant effect on load-bearing capacity of FDP. (2) FRC FDPs would not demonstrate higher load-bearing capacity than the FDPs without FRC.

MATERIALS AND METHODS

The materials used in this study are listed in Table 1. Seventy identically shaped laboratory-made FDP were fabricated on a zirconia model (Ice Zirconia, ZirkonZahn, Bruneck, Italy). The design of the framework corresponds to the situation of a three-unit inlay-retained bridge from the second premolar to the second molar replacing missing first molar. Besides, sanitary pontic design (2 mm space between pontic base and zirconia model) was used for missing mandibular first molar. The disto-occlusal inlay preparation (step: 3.0×2.0 mm; box: 1.5×3.5 mm; depth: 2.0 mm) on the second premolar, and the mesio-occlusal inlay preparation (step: 4.0×3.0 mm; box: 1.5×5.0 mm; depth: 2.0 mm) on the second molar were prepared with a milling unit (Zirkonzahn) (Fig. 1). Additionally, a space of 11 mm was left between the two abutments as it refers to the mesiodistal crown dimension of a mandibular first molar.

Table 1 Materials used in the present study

Material	Group code	Manufacturer	Composition	Lot no
Everstick C&B	FRP FRC1 FRC2	GC, Tokyo, Japan	Continuous uni-directional fiber: Resin: [a]PMMA, [b]Bis-GMA; filler: silanised E-glass fibres (E65 vol%)	1412081
G-Fix	RP FRP1 FRP2	GC	Resin Paste: [c]Bis-EMA and phosphoric ester monomers	1303011
EverX Posterior	PC	GC	Short fiber composite: [b]Bis-GMA, [a]PMMA, [d]TEGDMA, Short E-glass fiber filler, Barium glass 74.2 wt%, 53.6 vol%	1307292
Fibra Composite Bio-C	FB	Degos dental, Regenstauf, Germany	Fiber-reinforced high-performance polymer	1504302
PEEK Techno Med	PEEK	ZirkonZahn, Bruneck, Italy	High-performance medical polymer (polyetheretherketone)	4315
Temp basic	PMMA	ZirkonZahn	PMMA-based CAD-CAM blank	R010021

[a]PMMA: polymethyl methacrylate, [b]Bis-GMA: bis-phenol-A-diglycidyl methacrylate., [c]Bis-EMA: ethoxylated bisphenol-A dimethacrylate, [d]TEGDMA: triethyleneglycol dimethacrylate.

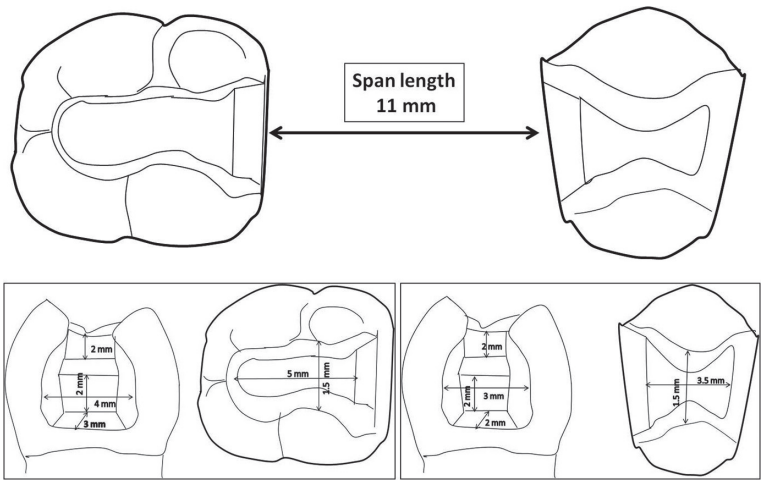


Fig. 1 Schematic representation of the zirconia model.
The disto-occlusal inlay preparation (step: 3.0×2.0 mm; box: 1.5×3.5 mm; depth: 2.0 mm) on the second premolar, and the mesio-occlusal inlay preparation (step: 4.0×3.0 mm; box: 1.5×5.0 mm; depth: 2.0 mm) on the second molar.

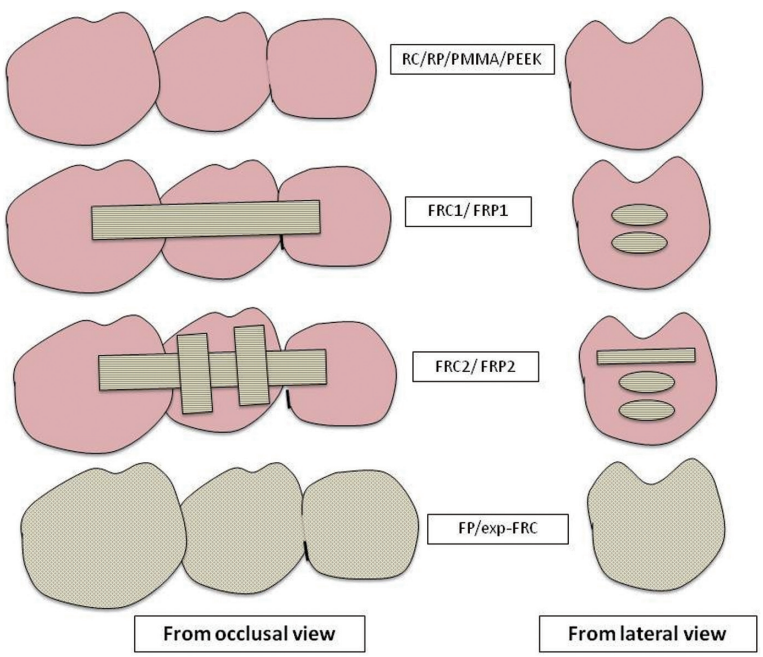


Fig. 2 Schematic representation showing different framework designs used in this study.

FDP preparation

The FDPs were fabricated according to different framework materials and their combinations (Fig. 2). Specimens were divided into ten groups (n=7/per group).

Group RC: made of discontinuous fiber composite (EverX Posterior, GC, Tokyo, Japan).

Group FRC1: made of discontinuous fiber composite (EverX Posterior, GC) with addition of two bundles of continuous unidirectional FRC (Everstick C&B, GC).

Group FRC2: made of discontinuous fiber composite (EverX Posterior, GC) with addition of two bundles of continuous unidirectional FRC (Everstick C&B, GC) and two pieces placed perpendicular to the main framework

(Everstick C&B, GC).

Group PMMA: made of CAD-CAM PMMA acrylic resin (Temp Basic, ZirkonZahn).

Group PEEK: made of CAD-CAM PEEK (PEEK Techno Med, ZirkonZahn).

Group FB: made of CAD-CAM FRC (Fibra Composite Bio-C, Degos Dental, Regenstauf, Germany).

Group RP: made of resin paste (G-Fix, GC).

Group FRP1: made of resin paste (G-Fix, GC) with addition of two bundles of continuous unidirectional FRC (Everstick C&B, GC).

Group FRP2: made of resin paste (G-Fix, GC) with addition of two bundles of continuous unidirectional FRC and two pieces placed perpendicular to the main framework (Everstick C&B, GC).

Group exp-FRC: experimental CAD_CAM FRC (epoxy-based E-glass FRC) (Stick Tech, GC) (Fig. 3).

In the groups with FRC and without FRC hand-made FDPs (RC, RP, FRP1, FRP2, FRC1, and FRC2) the resin paste/resin composite was polymerized incrementally for 20 s from each side (occlusal, buccal, and lingual) by LED light curing unit (LCU) (Elipar S10; 3M ESPE, St. Paul, MN, USA) with a power output of 1,200 mW/cm² (wavelength range: 430–480 nm). Additionally, FRC (Everstick C&B, GC) was placed as previously described in the groups section (Fig. 2). The connector dimensions of the FDPs were as follows: between second premolar and first molar, height 4.0 mm and width 5.0 mm, and between first molar and second molar, height 4.5 mm and width 5.5 mm. Following application of the veneer

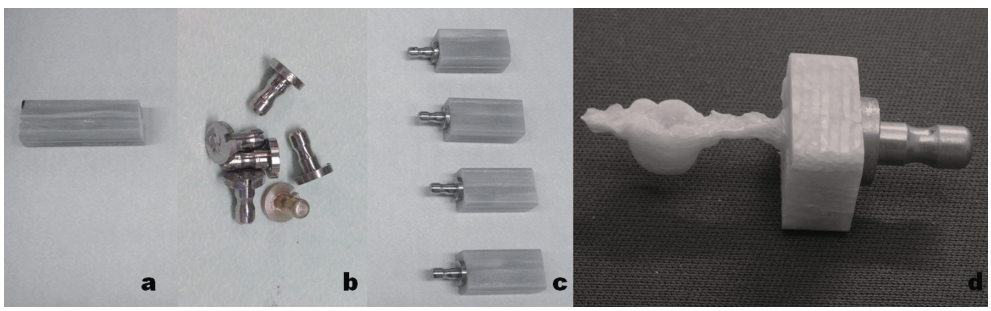


Fig. 3 Preparation of the experimental FRC blocks.
a: Prepared block, b: Metallic attachments for CAD-CAM, c: Blocks with attachments, d: The inlay-retained FDP prepared with CAD-CAM.

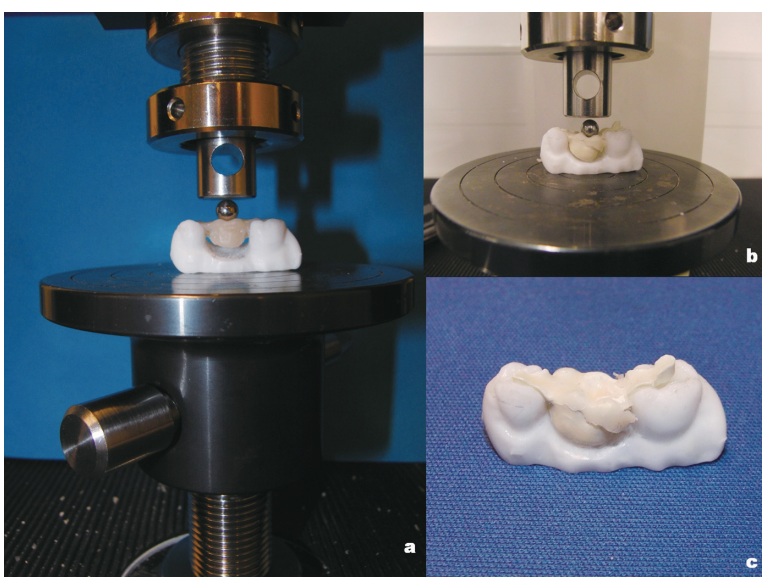


Fig. 4 Schematic illustration of load bearing capacity test.
(a) The specimen mounted in the universal testing machine for the test, (b) The image taken at the end of the test, (c) Fractured specimen after the test.

composite (Gradia-dentine, GC) on the FDPs, the completed FDP was post-cured in a vacuum light-curing device (Targis Power, Ivoclar-Vivadent, Schaan, Liechtenstein) for 30 min. A silicone molding was then produced by the use of transparent polyvinylsiloxane template (Memosil 2, Heraeus-Kulzer, Hanau, Germany) to standardize the dimensions of each FDP and to allow reproducible occlusal morphology. The specimens were dry stored for 24 h prior to luting.

In the CAD-CAM FDP groups (FB, PEEK, exp-FRC and PMMA), the optical impression of FDP was transferred to the Cerec 3 milling unit (Sirona Cerec MC XL; Sirona Dental Systems, Bensheim, Germany). Then, a three-unit FDP was created in the computer and saved in a file. The blocks were milled by the Cerec 3 milling (Sirona Cerec MC XL). Following application of the veneer composite (Gradia-dentine, GC) on FDPs, the silicone molding was superimposed; light cured for 20 s from each side (occlusal, buccal, and lingual) by LED unit and excess material was removed.

The occlusal thickness of the veneering material was set approximately at 1 mm in all of the FDPs. The adhesive surface of the inlay restorations were sandblasted (Cojet prep, 3M ESPE) with 30 μm silica-coated alumina particles (Cojet sand, 3M ESPE) under 0.3 MPa pressure for 10 s, followed by ultrasonically cleaning in distilled water for 5 min and drying. No additional pre-treatment was applied to the zirconia model. The three-unit FDPs were cemented onto the zirconia model with a dual curing-luting agent (Rely X Unicem App., 3M ESPE, Seefeld, Germany) according to the manufacturer's protocol. Excess luting cement was removed with a microbrush after the FDP was seated and light-cured from each side (occlusal, buccal, and lingual) for 20 s by LED unit. Following cementation, the specimens were stored for 15 min to allow the resin luting cement to set.

Load-bearing capacity test

Schematic illustration of load bearing capacity test was given in Fig. 4. Specimens were loaded with a universal testing machine (Lloyd instruments, Fareham, UK) until initial signs of damage could be observed at a crosshead speed of 1 mm/min. The load was applied by a 6 mm diameter steel contact ball, as previously described from the central fossa of the pontic[2,3,14]. The loading process was performed until fracture start of veneering composite, and initial failure was registered. In addition, initial failure was identified if at least two of the following conditions were detected: (1) a sharp decline in the load/displacement curve; (2) visible signs of fracture; or (3) audible emissions[22]. Fracture pattern of each loaded specimen was visually analyzed and categorized into four typical fracture patterns (connector fracture, delamination of veneering composite, splitting of FRC and pontic fracture).

Statistical analysis

The groups were initially analyzed using a two-way ANOVA and Tukey HSD tests. The factors analyzed were framework materials, FRC and material *vs.* FRC interaction. p-Values of less than 0.05 were considered to be statistically significant. When significant material *vs.* FRC interaction was detected, one-way ANOVA followed by the Tukey's *post-hoc* tests were performed ($p<0.05$). Additionally, statistical differences in fracture modes were investigated by chi-square tests at a significance level of $p<0.05$. All statistical tests were performed with IBM SPSS Version 20 (IBM, Armonk, NY, USA).

RESULTS

Load bearing capacity

The mean values and standard deviations for each group are shown in Figs. 5–7. ANOVA revealed that there were significant differences between load bearing capacities of the groups ($p<0.05$). The material used to fabricate FDP had significant effects on load bearing capacity values ($p<0.05$) (PEEK≥FB≥exp-FRC>RP≥RC≥PMMA material) (Fig. 5).

Statistical analysis revealed that FRC had significantly affected load-bearing capacity of the FDPs ($p<0.05$). According to this analysis, the load bearing capacity values were ranked as follows: prefabricated FRC (896.1±30.3 N) (Groups FB and exp-FRC)>addition of two bundles of unidirectional FRC and two pieces placed perpendicular to the main framework (677.2±27.6 N) (Groups FRC2 and FRP2)≥addition of two bundles of unidirectional FRC (614.8±26.8 N) (Groups FRC1 and FRP1)>no FRC (476.9±20.3 N) (Groups PMMA, PEEK, RP and RC) (Fig. 6).

The further analyses on individual FDP groups indicated the statistical ranking as follows: PEEK≥FRP2≥FB≥exp-FRC>FRP-1>FRC1≥FRC2≥RP≥PMMA≥RC (Fig. 7). While the highest load-bearing capacity was found for FRP2, with a mean value of 1,168 N; the lowest load-bearing capacity was found for PMMA

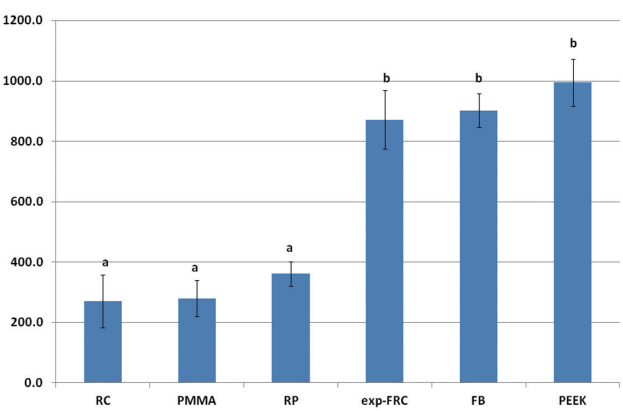


Fig. 5 Load bearing capacity test results according to the materials used (N).
*Means with same letter are not significantly different ($p>0.05$).

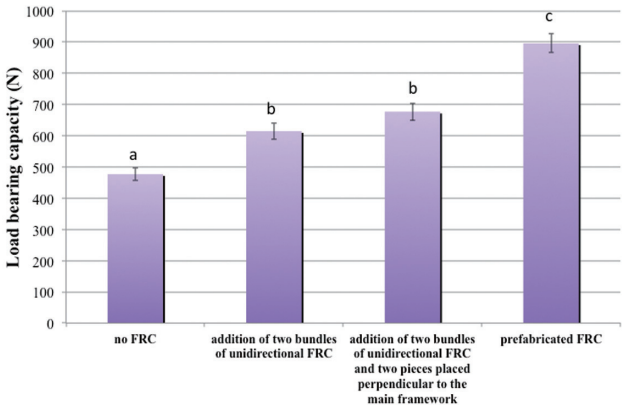


Fig. 6 Load bearing capacity test results according to the FRC addition to the framework (N).
*Means with same letter are not significantly different (p>0.05).

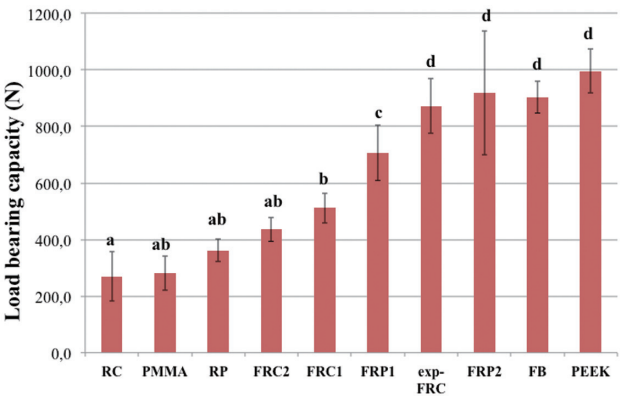


Fig. 7 Load bearing capacity test results of individual FDP groups with standard deviations (N).
*Means with same letter are not significantly different (p>0.05).



Fracture pattern	Pontic fracture	Delamination of veneer material	Connector fracture	Splitting of FRC
PEEK	0	0	7	0
PMMA	0	2	5	0
RC	7	0	0	0
FRC1	0	5	0	2
FRC2	0	6	0	1
RP	6	1	0	0
FRP1	0	5	0	2
FRP2	0	6	0	1
FB	0	7	0	0
Exp-FRC	0	0	0	7

Fig. 8 Fracture mode analysis according to the groups.

(206.6 N). There were no significant differences between load-bearing capacities of the groups PEEK, FRP2, exp-FRC and FB (995.5±78.1, 918.4±219.3, 889.1±106.6 and 903.1±55.5 N, respectively).

Fracture analysis

Chi-square test revealed significant differences between fracture patterns of the groups (p<0.05). The distribution of fracture patterns is shown in Fig. 8 (pontic fracture, delamination of veneer material, connector fracture and splitting of FRC). In Groups RC and RP, FDPs were fractured in a manner that cannot be repaired (catastrophic fracture) (7/7 and 6/7, respectively) (Fig. 8). In addition, in PEEK group, the type of fractures was connector fracture. Similarly, in PMMA group, the fractures were mostly in the connector part of the bridge (5/7). With the addition of FRC to the framework, the catastrophic pontic fractures decreased and delamination type of fractures increased (Fig. 8) (FRC1: 5; FRC2: 6; FRP1: 5; FRP2: 6; FB: 7).

Moreover, all of the exp-FRC FDPs showed splitting type of fracture in FRC.

DISCUSSION

This study addressed the effect of FRC on load bearing capacity of FDPs. In addition, the effects of novel FDP materials (discontinuous fiber composite, newly introduced resin paste and CAD-CAM materials) were tested. According to the results of this study, overall, the load bearing capacity of the material used significantly affected the FDPs, leading to the rejection of the first hypothesis (Fig. 5). The load bearing analysis test was preferred in the present study in order to test loading capacity of the inlay-retained FDPs with geometry close to that of clinical conditions and to produce clinically relevant fractures[23].

Previously, maximum bite forces have been reported to vary between 585 to 967 N depending on gender, age, cranio-facial morphology, occlusal factors, restorations and other parameters[24]. In addition, there are conflicting reports in literature about the optimal load-bearing capacity for successful inlay-retained FDPs in the posterior region[25-29]. In a previous study, Kohorst *et al.* investigated the load-bearing capacity of all-ceramic posterior four-unit FDPs with different zirconia frameworks and concluded that the load bearing capacities of the FDPs tested in that study were approximately 80 to 140% higher than the 500 N benchmark value[25]. In addition, it was reported that the FRC FDPs should be strong enough to resist the load bearing values between 500–900 N[26,27]. Moreover, a previous study compared the load-bearing capacity of all-ceramic resin-bonded three-unit inlay-retained FDPs and concluded that an initial load-bearing capacity of posterior all-ceramic inlay-retained FDP should be 1,000 N for long-term clinical success[28]. In accordance with previous reports, the load bearing capacity values of FRC FDPs were between 600–900 N in the present study (Fig. 6). Besides, Groups RC, PMMA, RP, FRC2 and FRC1 were below the benchmark value of 500 N (Fig. 7). Furthermore, FRP2, exp-FRC, FB and PEEK blocks exhibited load bearing values between 800 and 1,000 N (Fig. 7). Therefore, these restorations might be strong enough for clinical applications. However, the differences in parameters (design, used materials, pontic span, retainer preparation, and test set-up) of load-bearing studies make it difficult to compare the results with previous studies.

A previous study reported that CAD/CAM fabricated FDPs had higher load-bearing capacity than those fabricated by conventional procedures[29]. In the present study, except CAD-CAM PMMA group, all the CAD-CAM groups had higher load bearing capacity values than manually fabricated groups. Additionally, there were no significant differences between RC (269.9±60.2 N), PMMA (280±87.3 N) and RP (362.3±40.4 N) groups (Fig. 5). The material G-Fix (group RP) consists of Bis-EMA (ethoxylated bisphenol-A dimethacrylate), and a newly adopted monomer with flexible long-chain. In addition, according to the manufacturer, G-Fix has high elastic cross-linking monomer technology. Besides, it was previously reported that the elastic behavior of the materials could only be seen during stress release at higher stresses[30]. Therefore, to test its possible application as FDP material, G-Fix has been included in the present study. Additionally, group RC made of EverX Posterior consists of randomly oriented short E-glass fiber structure and the resin matrix (cross-linked Bis-GMA (bisphenylglycidyl dimethacrylate), TEGDMA (triethyleneglycol dimethacrylate) and linear PMMA)[31]. Although limited data is available in literature for the materials tested in the present study, the load bearing capacity test results of the groups might be explained with the microstructural differences and elastic behaviors of the tested FDP materials. Further analyses on mechanical properties of these structures should be conducted in order to clarify these correlations.

A previous study compared load-bearing capacity of CAD/CAM milled polymeric three-unit FDPs and reported that FDPs made of glass-ceramic demonstrated significantly lower fracture load than all resin FDPs[32]. Vita CAD-Temp cross-linked acrylate polymer had a load bearing value of 289±30 N, which is similar to the value of PMMA CAD block (280±87.3 N) tested in the present study. All in all, according to the manufacturer, the PMMA CAD blocks (Temp Basic, ZirkonZahn) used in the present study could be used as a short-term provisional restoration material.

In the current study, Groups FB (903.1±55.5 N) and exp-FRC (889.1±106.6 N) had statistically higher load bearing values than manually fabricated FRC-reinforced composite groups (FRC1 and FRC2; 511.6±53.6 N and 436.1±42.2 N, respectively). Previous studies have reported that industrially fabricated CAD/CAM materials have a homogeneous structure and thereby, a reduced risk of porosities and superior mechanical strength[33,34]. The dramatic difference in the present load bearing capacity values between the groups could be related with this phenomenon.

A previous study by Liebermann *et al.* evaluated the effects of different aging regimens and durations on physical and mechanical properties of different CAD-CAM materials (PEEK, hybrid material, composite resins, nanohybrid-composite resin and PMMA). As a result, this study recommended the use of PEEK for long-term restorations[35]. Similarly, according to the load-bearing test results of the present study, PEEK (995.52±78.1 N) could be used as an alternative FDP material to restorative resin-based materials. In addition, PEEK-based materials gather increasing interest as a possible alternative to titanium-based prostheses and implants in orthopedics and dentistry. The elastic modulus of PEEK is increased up to 18 GPa by the reinforcement of the material with carbon fibers. When the elastic modulus is similar to the bone tissue (10–18 GPa), it behaves mechanically in the same manner[36,37]. The elastic modulus of ceramics and metals are high, whereas the modulus of PEEK can be adapted by limiting the complications as a stress shield

barrier[19].

Of the resin-based materials used in this study, a short, discontinuous fiber composite (EverX Posterior) has been intended to be used for dentine replacement in large, deep and high-C factor design cavities. Furthermore, a previous study provided that EverX Posterior could be used in 4 mm increments in extensive posterior cavities to mimic the stress absorbing properties of dentine[38,39]. Since, these composites enable 4–5 mm thick increments to be cured in one step; they are time-saving and easy-handling composites[40,41]. However, in the current study, Group RC had low load bearing capacity value (269.9±60.2 N). This could be attributed to the quality of the manually processed bridges that might be highly affected by the operator, mixing proportions of the resin components, polymerization device, and duration of the polymerization. In addition, the presence of voids observed in RC material following load-bearing test, might have affected the fracture strength of these FDPs negatively. However, the effect of the FRC was evident necessitating rejection of the second null hypothesis. Besides, the mean values of groups FRC1 (511.6±53.6 N), FRC2 (436±42.2 N), FRP1 (717.8±126.6 N) and FRP2 (918.4±219.3 N) were significantly greater than those of the corresponding FDPs without FRC (Groups RC (269.9±60.2 N) and RP (362.3±40.4 N)). While RP group demonstrated low load bearing capacity values; Group FRP2, resin paste with fiber had similar values with Groups PEEK, exp-FRC and FB. Previous studies reported that FRC supported FDPs could be able to withstand posterior biting forces[42,43]. A previous study by Garoushi *et al.* evaluated the effect of FRC substructure on the static load-bearing capacity of particulate filler composite and concluded that supporting particulate filler composite by FRC substructure increased the load-bearing capacity of the material[43]. Moreover, the effect of FRC is also dependent on the fiber direction[41,44]. Therefore, to minimize the anisotropic behavior of unidirectional fiber reinforcement (Group FRC1 and FRP1); in groups FRC2 and FRP2, two additional FRC pieces were added in 90° angle to the main framework. FRP2 demonstrated significantly higher load bearing values when compared with non-fiber group (RP) (Fig. 6). Consequently, the results of the present study were in good agreement with studies[3,6,37,45,46] that showed the positive effects of FRC on properties of resin-based materials.

According to the fracture pattern analysis of the present experiment, it was revealed that there were significant differences between fracture modes of the groups (Fig. 8). Analysis of the failure patterns of FRC-FDPs demonstrated that Group RC and RP showed pontic fracture following loading. Additionally, fiber addition to the framework changed the behavior of the fracture pattern from pontic fracture to delamination of veneer material. FRC substructure might have provided an ability to slow or arrest crack propagation and could result in delamination of resin-based material from the underlying FRC framework[2]. Furthermore, in the present study, the fracture pattern analysis results supported load bearing capacity test results. In other words, with the increase in load bearing values, the mode of failure changed from pontic fracture (non-restorable) to delamination of veneer material (restorable). Since the distribution of the fibers was parallel to the exp-FRC bridge framework, the fractures showed splitting characteristic in the pontic region. In Groups PEEK and PMMA, most of the fractures occurred in connector region. This region was reported to be the weakest link of the inlay-retained FDPs[41,47]. Similarly, a previous study by Fischer *et al.* indicated that the connector area between abutment and pontic of bridges is critical region where fractures typically occur[48]. The differences between fracture mode of the groups RC, RP and PMMA, PEEK could be related with the fabrication methods of the FDPs.

Eventually, the design of this *in vitro* study has several limitations to simulate clinical conditions. The first limitation was the use of rigidly mounted zirconia based abutments instead of natural teeth with periodontal ligament simulation. The primary disadvantage of rigidly mounted abutments is the lower elastic modulus of the zirconia model than natural teeth. The second limitation was the limited number of specimens tested. Another limitation concerns the fact that aging process could be useful to understand clinical behavior of these bonded bridges. Further studies are needed to clarify the effects of thermomechanical loading on tested FDP materials.

CONCLUSIONS

Within the limitations of this study, the following conclusions can be drawn:

1. PEEK, FRP, exp-FRC and FB FDP groups exhibited higher load-bearing capacity values than the other groups.
2. Due to their inferior load bearing capacity values; Groups PMMA, RP, RC, FRC1 and FRC2 FDP might be suggested only for short-term restorations.
3. FRC had significantly affected load-bearing capacity of tested inlay-retained FDPs.

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CONFLICTS OF INTEREST

The author Pekka K. VALLITTU consults GC in training and RD. Other authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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