Silica-Nylon Reinforcement Effect on the Fracture Load and Stress Distribution of a Resin-Bonded Partial Dental Prosthesis

Aline Silva Firmino, DDS, MSc
João Paulo Mendes Tribst, DDS, MSc, PhD
Leonardo Jiro Nomura Nakano, DDS, MSc
Amanda Maria de Oliveira Dal Piva, DDS, MSc, PhD
Alexandre Luiz Souto Borges, DDS, MSc, PhD
Tarcisio José Arruda Paes-Junior, DDS, MSc, PhD

This study investigated the influence of silica-nylon reinforcement on the stress distribution and fracture load of a resin-bonded fixed partial dental prosthesis (RBFDP). Three-unit RBFDPs (N = 60) were inserted between the first premolar and the first molar of a maxillary model. The groups were divided according to the nylon reinforcement (n = 20/group): conventional fixed prosthesis (without reinforcement), prosthesis with silica-nylon reinforcement positioned vertically, and prosthesis with silica-nylon reinforcement positioned horizontally. Half of the specimens were tested after 24 hours in a universal testing machine until fracture (1,000 kgf; 1 mm/minute) to determine the single load to fracture. The other half was submitted to mechanical aging during 10⁶ cycles (100 N, 2 Hz), totaling 6 groups (n = 10/group). The results were analyzed by two-way analysis of variance (ANOVA; α = 5%). The stress distribution for non-aged groups was simulated using finite element analysis. The numeric prostheses were modeled similarly to the in vitro assay. ANOVA showed no statistical difference between groups (P < .05) for load to fracture. However, the use of the reinforcement provided stability even after the failure, as the parts did not separate. The computational analysis showed similar biomechanical behavior among the groups. The use of the nylon reinforcement does not influence the fracture load or the stress distribution, but it does enable the prosthesis to remain in position after failure. Int J Periodontics Restorative Dent 2021;41:e45–e54. doi: 10.11607/prd.4347

Fixed dental prostheses (FDPs) are a treatment option for patients who have had dental loss and are unable or unwilling to receive an implant-supported prosthesis. The treatment performed with implant-supported prostheses is considered more invasive, with greater clinical and laboratorial stages that lead to long treatments. FDPs are more comfortable compared to removable partial dentures due to dental support. In most cases, FDPs present better esthetics, are less invasive than dental implants, and often lower immediate cost. However, the need for procedures such as replacement of the FDP and endodontic treatment, as well as post, core, and new retainer crowns, can increase the treatment costs. Its usual configuration presents teeth as abutments in each end of the edentulous space, which attributes its prosthetic support. With the development of restorative materials and adhesive dentistry, resin-bonded FDPs (RBFDPs) have shown promising results. Among the materials used to manufacture RBFDPs, composite resin stands out as being less abrasive than dental ceramics for opposing dentition; however, it possesses less strength. In order to minimize the mechanical problems inherent to composite resin, different materials have been used as reinforcement, such as carbon, aramid,
glass fibers, nylon, metal wire, and others.\textsuperscript{3–5} Reinforced composites have improved characteristics, obtaining acceptable values for rigidity against masticatory forces, low weight, and a favorable elastic modulus.\textsuperscript{6} Despite this, there are few reports of chemically compatible materials that do not modify esthetics and are easy to handle for use in composite resins.

In 2012, a nylon mesh coated with silica was developed and used to reinforce the total denture base.\textsuperscript{7,8} The authors observed favorable results with higher flexural strength values than conventional acrylic resin. Its creators wanted to associate the favorable properties of nylon with silica, which had the function of increasing the chemical bonding of the mesh to the polymeric materials. This silica-nylon reinforcement was investigated in another study\textsuperscript{8} that evaluated its behavior when used with bis-acryl resin, achieving promising results for fracture strength.

Because of the promising results obtained with this nylon mesh, the present study evaluated its influence on the load to fracture of composite resin adhesive FPDs and its stress distribution. The hypothesis of the study was that the presence of the reinforcement would improve the mechanical properties of FPDs in the short and long term.

Materials and Methods

RBFPD Fabrication

A maxillary dental arch model was scanned (Ceramill Map 300 scanner, Amann Girrbach), generating a stereolithographic (STL) file. The right posterior region was selected due to absence of the second premolar. The first premolar was prepared with a Class II cavity on the occlusal surface ($5 \times 2 \times 2$ mm) as well as on the distal proximal aspect ($4 \times 2 \times 2$ mm); the first molar was prepared with a Class II cavity on the occlusal surface ($8 \times 2 \times 2$ mm) as well as on the mesial proximal aspect ($4 \times 3 \times 3$ mm). The 3D models of both prepared teeth were 3D printed (ProJet 1000, 3D Systems) in a thermoplastic polymer (acrylonitrile butadiene styrene). Then, the printed teeth with the cavity preparations were molded with the addition of polymerized silicone (Elite HD+ regular body, Zhermack; and Flexitime correct flow, Kulzer), and the mold was poured with epoxy resin (Valglass), totaling 60 premolars and 60 molars (Fig 1). Each abutment tooth was demarcated 2 mm from the cementoenamel junction, and the root portion was covered with red wax. Each set of epoxy resin abutments was included in a silicone mold ($35 \times 20 \times 20$ mm) with the aid of a dental delineator (Bio-Art, B2Brazil) containing a solution based on polyurethane resin (F160 resin, Axson). After polymerization of the polyurethane resin, the teeth were removed from the artificial alveoli and cleaned with hot water to remove the wax. Polyether-based elastomer (Impregum F, 3M

Fig 1 Sample preparation and monotonic test. (a) Impressed teeth and final prosthesis. (b) Simulated periodontal ligament. Examples of (c) horizontal and (d) vertical nylon reinforcement insertions on the cavities. (e) Load to fracture test.
ESPE) was inserted into the alveoli to simulate the periodontal ligament, and the teeth were introduced under digital pressure until the 2-mm mark above the cementoenamel border coincided with the surface of the polyurethane resin.

The 60 experimental models were randomly distributed into one of three groups according to the silica-nylon reinforcement (n = 20 per group; Table 1): the control group, with a conventional fixed prosthesis (without reinforcement), or an experimental group, where the prosthesis with silica-nylon reinforcement was positioned vertically or horizontally (Fig 1). Half of the specimens from each group were submitted to mechanical aging (total of 6 groups, n = 10 each), and all specimens were tested in a universal testing machine until fracture to determine the single load to fracture.

To prepare the prostheses, the reinforcements were placed inside the proximal cavity of each inlay preparation and covered by portions of photoreactive composite resin (Nanolab Z, Wilcos). The resin was deposited in 2-mm increments and put into an oven for photoactivation, performed using a photoemitter (Visio Beta Vario, 3M ESPE).

### Aging Protocol

Aged groups were submitted to mechanical cycling during $10^6$ cycles at 2-Hz frequency. All specimens were vertically loaded onto the occlusal surfaces of the pontic with 100-N force (mechanical cycler ERIOS 1000 Plus). The loading was applied using a round, stainless steel piston with a 6-mm radius. The specimens were checked for cracks or fracture every 100,000 cycles after each loading phase through the transillumination technique. Failure was defined as large chippings, cracks, or resin bulk fracture.

### Single Load-to-Fracture Test

All specimens were subjected to a single load-to-fracture test using a universal testing machine (1 mm/minute$^{-1}$, 1,000-kgf load cell; DL-1000, EMIC). The non-aged specimens were tested 24 hours after placement, while the others underwent testing following the above aging protocol. The specimens were fixed in the horizontal plane with no inclination, and the load was applied vertically until failure using the same indenter used in mechanical aging (Fig 1). The maximum load to fracture was recorded in Newtons (N) for each sample. A radiograph was taken of each fractured prosthesis, and the prosthesis was visually inspected with a stereomicroscope (SteREO Discovery.V20, Zeiss) by a single operator (A.S.F.).

### Statistical Analysis

Statistical analysis was performed using Minitab software. The load-to-fracture data were subjected to two-way analysis of variance (ANOVA) with $\alpha = 5\%$.

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<table>
<thead>
<tr>
<th>Table 1 Mean ± SD Load-to-Fracture Values for Each Group</th>
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<tbody>
<tr>
<td>Group</td>
</tr>
<tr>
<td>P</td>
</tr>
<tr>
<td>No aging</td>
</tr>
<tr>
<td>Aging</td>
</tr>
<tr>
<td>RPV</td>
</tr>
<tr>
<td>No aging</td>
</tr>
<tr>
<td>Aging</td>
</tr>
<tr>
<td>RPH</td>
</tr>
<tr>
<td>No aging</td>
</tr>
<tr>
<td>Aging</td>
</tr>
</tbody>
</table>

P = conventional fixed prosthesis without reinforcement; RPV = prosthesis with silica-nylon reinforcement positioned vertically; RPH = prosthesis with silica-nylon reinforcement positioned horizontally.
Finite Element Analysis

Preprocessing
The 3D model was generated based on the STL file from the in vitro sample preparation (Fig 2). The file was exported to modeling software (Rhinoceros v 5.0 SR8, McNeel North America) in a polygon mesh. The next step was using RhinoResurf (Resurf), a reverse-engineering tool that gives computer-aided–design software the ability to reconstruct NURBS (non-uniform rational basis spline) surfaces from a mesh or point cloud with specified precision.9 Next, 3D volumetric models of molar and premolar teeth were created. The FDP was created based on the in vitro sample dimensions. The model was replicated in three models according to the absence of reinforcement (control) and reinforcement position (horizontal and vertical). The cement layer was modeled with 70-μm thickness based on the external surfaces of the fixed prosthesis and on the external surfaces of Class II cavity preparations.

Processing
Three different prosthesis geometries were obtained to evaluate the silica-nylon reinforcement effect. The three models were inserted into a polyurethane block. Polyurethane mimics bone tissue and is widely used in in vitro and in silico (mathematical) studies due to its elastic modulus (E = 3.6 GPa), which has been validated as a substitute for human bone tissue.10 The resin cement had E = 6 GPa,9 Poisson ratio (ν) = 0.30, and linear shrinkage = 2.7%. The models were imported through STEP (Standard for the Exchange of Product Data) format into the analysis software (ANSYS 17.2), in which they were divided into finite element mesh. The mechanical properties of each structure were inserted into the analysis software (Table 2),11 and each material was considered isotropic, elastic, or homogenous. No-separation contacts were considered between restoration/resin cement and resin cement/tooth.9 The contact between the abutment tooth and the periodontal ligament was considered perfectly bonded. The model fixation in all groups occurred at the base of the polyurethane block with zero fixed nodal displacements, and an axial load of 100 N was applied to the occlusal surface of the pontic (Fig 3). A mesh convergence test (10%) was performed to guarantee that the mesh would not interfere with the results.9,12,13 The thermal expansion approach was used to simulate the polymerization shrinkage effects of adhesive layers and bulk fill composite, assuming a one-degree drop in temperature, thereby promoting the adhesive layer shrinkage and stress generation at the tooth–restoration interface.13 Maximum principal stress criteria were used to evaluate the results.

Results

Single Load to Fracture Test
Two-way ANOVA showed no statistical difference between the mean fracture load for the reinforcement factor or aging (Table 3). Failure

![Fig 2 3D model. Volumetric geometries used to perform the static structural analysis, mesh division, and boundary conditions. The system fixation occurred in the base of the polyurethane block, and the axial load was applied on the prosthesis occlusal face.](image)
Fig 3  (a to f) Representative failed samples under ×7.5 magnification in stereomicroscope. Control groups (a) with and (b) without aging; groups with vertical reinforcement (c) with and (d) without aging; and groups with horizontal reinforcement (e) with and (f) without aging. Radiographic images of representative samples (g) with vertical reinforcement, (h) with horizontal reinforcement, and (i) without reinforcement.
analyses showed that all prostheses failed with the same pattern in the region of the connector located between the first and second premolars. The prostheses remained cemented even after fracture; however, groups with reinforcement presented the complete separation of the prosthesis (Fig 3).

Finite Element Analysis

The colorimetric maps of the maximum principal stress suggest that the tensile stress concentration is similar between the evaluated groups (Fig 4). The nominal values were close to the convergence limit of 10% obtained when defining the amount of final elements that formed the mesh. Based on the stress peaks, it is possible to assume that the probability of fractures occurring in the region of connection with the premolar during axial loading is greater than in the molar, independent of the evaluated group (Fig 4).

**Discussion**

This study evaluated the influence of using a silica-nylon reinforcement on the load to fracture and stress distribution of an RBFPD. The study hypothesis was rejected since no statistically different values were found for the load necessary to fracture the prosthesis, and there was no discrepancy in the stress concentration between groups. In spite of this, it is noteworthy that the groups that received the reinforcement (regardless of position) did not allow the fragments to separate, as occurred in the control group.

The need for adequate strength to withstand masticatory loads has propelled developing studies that seek to improve the mechanical properties of acrylic resins. Reinforced materials tend to minimize the stress level in the tooth-restoration interface due to the lower elastic modulus than seen in ceramics and metals. Therefore, less stress is concentrated in the interface, preventing the restoration from adhesive failures. The main failure reported for FDPs in metal was debonding; however, since the adhesion technologies and dental materials were...

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**Table 2 Elastic Modulus (E) and Poisson Ratio (ν) of Materials Used in the Finite Element Analysis**

<table>
<thead>
<tr>
<th>Material</th>
<th>E (GPa)</th>
<th>ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite resin*</td>
<td>12.825</td>
<td>0.256</td>
</tr>
<tr>
<td>Silica-nylon reinforcement*</td>
<td>1.9</td>
<td>0.17</td>
</tr>
<tr>
<td>Epoxy resin*</td>
<td>2.31</td>
<td>0.49</td>
</tr>
<tr>
<td>Polyurethane*</td>
<td>3.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Polyether*</td>
<td>0.068</td>
<td>0.45*</td>
</tr>
</tbody>
</table>

*Data obtained from the technique of pulsed excitation (UNESP database).

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**Table 3 Results of Two-Way Analysis of Variance**

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforcement</td>
<td>2</td>
<td>6,748</td>
<td>3,374</td>
<td>0.46</td>
<td>.63</td>
</tr>
<tr>
<td>Aging</td>
<td>1</td>
<td>28,698</td>
<td>28,698</td>
<td>3.90</td>
<td>.06</td>
</tr>
<tr>
<td>Reinforcement*aging</td>
<td>2</td>
<td>21,083</td>
<td>10,542</td>
<td>1.43</td>
<td>.24</td>
</tr>
<tr>
<td>Error</td>
<td>53</td>
<td>390,094</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>58</td>
<td>447,483</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

df = degrees of freedom; Adj SS = sum of squares; Adj MS = mean of squares.
Fig 4  Maximum principal stress generated in the fixed prosthesis according to the position of the silica-nylon reinforcement.
improved, the prosthesis and retainer design are suggested as having greater influence on the restoration success.15 Lateral forces are more related to the adhesive failures than the axial load directly transmitted to the tooth from the occlusal rest and chamfer.15 The stress-distribution results under axial load supported these findings since the stresses were concentrated in the connector area and not on the adhesive interface between prosthesis and tooth, regardless of the presence of a reinforcement.

Different materials have been used as structural reinforcement, such as glass fibers,16 polyester,17 and silica-nylon.8 Similar to the samples simulated in the present study, Göhring et al18 studied reinforced fixed prostheses in which the abutment teeth received partial preparation, though the authors used fiberglass as their material of choice. The results were satisfactory because the restorations were preserved in an oral environment after 1 year. Composite resins reinforced with fiberglass present improved mechanical characteristics, obtaining higher load-to-fracture values, good esthetics, low weight, and favorable elastic moduli.5,16 The advantage of using a silica-nylon reinforcement vs fiberglass would be its low cost and easier handling, in addition to adequate adhesion with composite resins.8 Despite this, silica-nylon reinforcement was not able to significantly increase fracture load values during the performed test. In addition, the presence of the reinforcement showed a similar failure origin but with the advantage of maintaining the prosthesis in position, providing the patient and clinician more time before manufacturing a new RBFDP.

Fairhurst et al19 and Wiskott et al20 affirmed that failure due to fatigue is explained by the development of microscopic cracks started in stress-concentration areas. Due to the recurrence of masticatory loads, these cracks fuse with pre-existing cracks, weakening the material structure. In this way, the fracture results from several cycles of compressive forces that decrease the material’s strength. As a result of this, the groups underwent mechanical cycling in an attempt to simulate the repetitive masticatory effort, thus inducing structural changes in the restorative material and the possible appearance of defects.21,22 The preparation of RBFDPs with composite resin is very promising, since mechanical fatigue was not able to significantly reduce the load to fracture in any of the evaluated groups. The results correspond to the maximum load necessary to fracture the restorations, and all evaluated prostheses showed a durable mechanical performance, with consistent long-term restoration resistance.

Likewise, previous studies have shown favorable mechanical results for incorporating silica-nylon in acrylic7 and bis-acryl resin.8 Finite element analysis was performed herein for the three prosthesis configurations used (vertical, horizontal, and absence of reinforcement), illustrating the mechanical response to the load in the laboratory test (Fig 4). The variables found during the mathematic simulation in the in vitro assay were reduced due to an absence of internal defects in the resin, accumulated residual stresses in the structure of each prosthesis, and ideal standardization of the cement thickness.12

Using a computer-aided design software, it was possible to trim the 3D design of the reinforcement mesh so that it fit perfectly into the cavity preparations and was fully coated by the resin. Maximum principal stress was selected as the failure criterion due to the friable material characteristics of the composite resin, failing by tensile stress during load application.12 In this way, the results obtained in the finite element analysis corroborated with the laboratory findings, showing similar stress maps between the groups.

Regarding the retainers for posterior prostheses submitted to heavier occlusal demand, a previous paper has already investigated different designs and observed that the most stressed area is the connector,15 which is corroborated by the results presented herein. This paper also demonstrated that conservative preparations reduce the size of the indirect material and increase the stress concentration. For that reason, some clinicians avoid the use of intracoronal retainers in posterior RBFDPs and prefer to use large preparations, increasing the strength of the restoration. Herein, only an inlay-type design (mesial-occlusal-distal cavities) was evaluated (considering that the maximum amount of tooth tissue should be preserved), aiming to investigate the effect of inserting a fiber reinforcement in the prosthesis.
All prostheses failed with the fracture origin in the connector area, corroborating with the finite element analysis results. All groups showed the same preparation geometry with a conservative approach for the dental tissue; however, this retainer design promoted a fragile area located in the connector region.

The corroboration of in vitro and in silico results is a form of validating the 3D mathematic model, enabling the assumption that the results correspond with reality and can be extrapolated, despite the limitations of a theoretical study. With a valid model, new studies can be conducted, and therefore other variables can be analyzed with the objective of reducing the stress in critical areas, like the prosthetic connector. Thus, new studies with composite resin in a less extreme situation than the one studied herein (pontic in the posterior region fixed only by inlays), or even with a new reinforcement configuration, are necessary. Also, further studies comparing anterior and posterior RBFDPs must be performed and compared carefully. The configuration of the simulated specimen will prevent a patient with a weakened prosthesis from experiencing esthetic damage, even in the case of fracture, due to nondisplacement of the pontic. Thus, the prosthesis could be held in place until a new restoration is made, without exposing the edentulous space and with a lower risk of exposing sharp areas capable of injuring the soft tissues in the mouth.

Conclusions

Based on this study proposal, it can be concluded that incorporating the experimental reinforcement did not influence the prosthesis maximum load to fracture or influence the stress distribution, even though the fractured parts were maintained in position by the silica-nylon reinforcement.

Acknowledgments

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References


