**In-vitro** performance of posterior fiber reinforced composite (FRC) bridge with different framework designs

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This study aimed to investigate the effect of various framework designs on the failure of posterior fiber reinforced composite (FRC) bridges and assess the post crack performances of the repaired prostheses. Thirty samples were prepared into three different groups of framework designs: cuspal support (CS), anatomic features (AF) and circular reinforcement (CR). All specimens were subjected to static loading test and acoustic emission analysis. Significant differences were found in the load and time of initial failures among the three groups (p<0.001). CS was identified as the optimum framework design. Samples with composite delamination at the pontic area were selected and repaired with a clinically simplified protocol. Significant differences were also observed between the repaired and original FRC bridges (p=0.01). The performance of these prostheses was highly dependent on the framework design and the perspective of repairing FRC bridges may warrant future investigations.

**Keywords**: Acoustic, Composite repair, Dental prosthesis design, Fixed partial denture, Prosthodontics

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**INTRODUCTION**

Advancements in dental materials offer various treatment modalities for the replacement of missing teeth. Material selection for posterior dental bridges still involve all metal, ceramics, metal ceramics and resin composite such as fiber reinforced composite (FRC)⁷. The selection of material depends on the indications and the condition of the abutments, functional requirements, and the patient’s esthetic demands. For example, the usage of full metal prostheses is restricted in non-esthetic zone and in limited inter-restorative spaces where minimal tooth preparation is required⁶. The preference for FRC in the construction of dental bridges gained popularity as it adopts the principle of minimally invasive dentistry and excellent esthetics⁸. The clinical performance of an FRC bridge seems to be satisfactory with a success rate of 97% at 4.7 years, and the commonly observed failure involves fracture of the veneering material or delamination at the pontic area⁹. The leading factor causing such failure is the lack of a substructure support that can be reinforced by placing additional FRCs within the framework. Therefore, various modified framework designs were proposed with their respective ideologies; in the latest review, a design with a combination approach was recommended to reinforce the pontic area⁹.

Prior in-vitro studies on framework designs indicated final failures after mechanical loading, along with detailed evaluation of failure patterns⁹. Final failure loads were reported to be 27% to 46% higher than the values obtained from initial failure and often surpassed the physiological masticatory forces⁸. Hence, identifying initial failure loading values can prevent overestimation and increase clinical relevance. There are three methods in determining the initial failure load: 1) visually identifying the first crack, 2) observing the first drop in load displacement graphs and 3) audible emission from the initial crack which can be detected via acoustic emission (AE) analysis¹⁰. Following Dyer’s criteria, any two of the three described criteria can be considered as initial failure. Previous studies on the initial failure of FRC bridges obtained their results from the first drop of the load-displacement curve and visible fracture signs⁸,¹¹, but these indicators can be unreliable because of the subjectivity in the visual inspection of these first signs of damage. A more accurate method entails detecting the AE events gathered from the microstructural changes in the FRC bridge¹². When an external force is placed on the material, the formation of microcracks or microfractures releases audible stress waves which are then recorded by sensors in the form of energy. AE is a real-time non-invasive method for recording and analyzing the collected data.

Considerations regarding FRC bridge repair were not widely explored in previous literature. Defective composite restorations should be repaired whenever possible, and replacement of the entire restoration should be kept as the final option¹³. Several repair techniques were suggested, but a repair protocol for the FRC bridge is yet to be recommended.

To the best of our knowledge, no studies have investigated the initial failure loads of these modified framework designs of various combinations. This study aimed to examine the effect of different framework...
Table 1 Materials used in the study

<table>
<thead>
<tr>
<th>Material</th>
<th>Brand</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Reinforced Composite (FRC)</td>
<td>EverStick C&amp;B</td>
<td>StickTech, Turku, Finland</td>
</tr>
<tr>
<td>Packable composite</td>
<td>G-ænial Posterior</td>
<td>GC, Tokyo, Japan</td>
</tr>
<tr>
<td>Flowable composite</td>
<td>G-ænial Universal Flo</td>
<td>GC</td>
</tr>
<tr>
<td>Etchant</td>
<td>DENU Etch 37</td>
<td>HDI, Seoul, Korea</td>
</tr>
<tr>
<td>Bonding agent</td>
<td>G-Premio BOND™</td>
<td>GC</td>
</tr>
<tr>
<td>Silicone impression template</td>
<td>DENU Trans Sil</td>
<td>HDI</td>
</tr>
<tr>
<td>Polymethyl methacrylate</td>
<td>Kemdent</td>
<td>Kemdent, Wiltshire, UK</td>
</tr>
<tr>
<td>Polyvinylsiloxane impression material</td>
<td>Aquasil Ultra LV</td>
<td>Dentsply, Milford, DE, USA</td>
</tr>
<tr>
<td>High-speed white stone</td>
<td>Dura White Stone</td>
<td>Shofu, Kyoto, Japan</td>
</tr>
<tr>
<td>High-speed fine grit diamond bur</td>
<td>Shofu Diamond Bur FG, #F102R</td>
<td>Shofu</td>
</tr>
<tr>
<td>Intermediate monomer resin (IMR)</td>
<td>StickResin</td>
<td>StickTech</td>
</tr>
</tbody>
</table>

FRC bridges fabrication

Premolar inlay cavities were prepared in dimensions of…

MATERIALS AND METHODS

Experiment material

The core material for this study was the EverStick C&B (StickTech, Turku, Finland) used in the construction of different framework designs. Materials used in the study were listed in Table 1.

Sample preparation

Thirty sound mandibular first premolars (single-rooted) and first molars (distinct diverged two roots) were meticulously collected and cleaned. Composite built-up (G-ænial Posterior, GC, Tokyo, Japan) was performed on the root surface of the first pair of premolar and molar to reshape the roots and eliminate irregularities after etched (15 s, DENU Etch37, HDI, Seoul, Korea), rinsed and bonded with light curing bonding agent (G-Premio BOND™, GC). The roots were placed in a transparent container filled with transparent silicone impression material (DENU Trans Sil, HDI) to construct a customized silicone template. Composite built up of the remaining roots of premolars and molars according to the prepared template and standardized dimensions of the premolar and molar roots were achieved.

All premolars and molars were soaked in a wax bath of 100°C twice to obtain approximately 0.5 mm of thickness around the roots. A premolar and molar pair with a distance of 7.0 mm was embedded in freshly mixed polymethyl methacrylate (PMMA) (Kemdent, Wiltshire, UK) up to 1.0 mm below the cementoenamel junction (CEJ). The PMMA acrylic was contained in a silicone mold of 2.0×2.0 cm. The wax spaces were replaced with polyvinylsiloxane (PVS) impression material (Aquasil Ultra LV, Dentsply, Milford, DE, USA) to simulate the presence of a periodontal ligament (PDL). The teeth embedding procedure and PDL simulation are described in Fig. 1.

Fig. 1 Teeth embedding procedures and PDL simulation.
2.0×1.0 mm for a disto-occlusal proximal step and 2.0×3.0 mm for a disto-occlusal proximal box with a buccolingual width of 3.0 mm. Molar inlay cavities were prepared in dimensions of 2.0×2.0 mm for a mesio-occlusal proximal step and 2.0×4.0 mm for a mesio-occlusal proximal box with a buccolingual width of 3.0 mm.

The samples were randomly divided into three groups before framework placement. The cavities were etched with 37% phosphoric acid and rinsed. A thin layer of a bonding agent was applied on all the cavity surfaces and cured for 15 s. Flowable composite (Genial Universal Flo, GC) was placed on the cavity floors. While they remained uncured, the substructure FRCs (EverStick C&B, StickTech) were placed according to the respective framework designs (Fig. 2).

The cuspal support (CS) group consisted of two horizontal FRCs from cavities to cavities topped with a perpendicularly placed short (5 mm) FRC beneath the future buccal and lingual cusps of 2nd premolars. The anatomical featured (AF) group contained two horizontal FRCs from cavities to cavities with a short FRC placed perpendicular and in between the two horizontal FRCs. The cross section of this framework represents the anatomic outline of a 2nd premolar. The 3rd framework design was made up of two horizontal FRCs from cavities to cavities with a parallelly placed short FRC which was stretched out circulating the main horizontal FRCs, hence, known as the circular reinforcement design (CR).

Each FRC placed was initially light cured for 5 to 10 s to secure the FRC position before placing the next FRC. Flowable composites were placed in between the FRCs before the frameworks underwent 40 s of final curing. Another thin layer of the flowable composite covering the external surfaces of the FRC framework was placed and cured for 20 s.

The pontic anatomy was built up with a packable composite following the morphology of the second premolar with a flat cuspal angle. A transparent silicone template was fabricated over the first pontic. Subsequent pontics were built up following the template so as to standardize the shape and size of the pontics for all samples. Finally, all FRC bridges were finished with high-speed white stone (Dura White Stone, Shofu, Kyoto, Japan) and polished with composite polishing burs (EVE DiaComp Plus Twist, Smart, Israel).

**Loading and AE Test**

The samples were stored in distilled water (37°C) for 72 h and underwent thermocycling (6,000 cycles, alternating between 5°C and 55°C with a dwell time 20 s and transfer time of 5 s). Then, the samples were loaded (v=1 mm/min) with a custom-made stainless-steel jig that consists of a 6 mm diameter ball end. The jig was attached to the upper compartments of the Universal Testing Machine (Model: AG-X Series, SHIMADZU, Kyoto, Japan). The ball was positioned approximately 1–2 mm above the buccal cusp of the pontic. A thin aluminum foil of...
0.3 mm thickness was placed over the pontic area to reduce excessive stress forces by peak loading. Failure detention was recorded at 10% loss of maximum force. The AE analysis and static loading test were conducted concurrently. Prior to testing, two AE sensors were attached to the specimen mesially and distally with an electron wax coupling agent. These SR150M AE Sensors (Soundwel Technology, Guangzhou, China) have a frequency bands ranging from 60 kHz to 400 kHz with the resonant frequency of 150 kHz and sensitivity peak more than 75 dB. The sensor size is 19 mm in diameter and 15 mm in height which matched the size of the prepared samples. A trial run of the AE testing was performed using a pencil-lead fracture test before loading. Sensors that failed to detect the AE events were replaced. The final set up is shown in Fig. 3.

During loading, the AE signals emitted from the crack within the FRC bridges were collected by the PCI-2 AE System. The data were stored in AEwin™ Software. Preamplifiers manufactured by Soundwell Technology with a 40 dB gain and a bandpass of 100 kHz to 2 MHz were used to amplify any signal higher than the threshold value set at 40 dB. All the specimens were visually inspected after the loading and AE test, and their mode of failures were recorded.

Post crack performance
The group with the highest initial failure load was selected for the post crack performance test. FRC bridges with the most typical type of clinical failure (delamination of the external composite at the pontic site) were chosen for the next phase of laboratory testing. The fractured sites were air-dried and carefully examined under a microscope. Samples with composite cracking involving one or both connectors were excluded. Finally, six samples that met the criteria were selected and stored in distilled water prior to the repair protocol.

The samples were dried for 20 s to expose the composite surfaces, and FRCs were roughened with fine-grit diamond bur of 46 µm mean grit size (Shofu Diamond Bur FG, #F102R, Shofu). A thin layer of intermediate monomer resin, IMR (StickResin, StickTech), was applied on the FRC surfaces. The FRCs were then kept in the dark for 5 min to facilitate reactivation. The FRCs were later cured for 40 s. The same external composite built up was performed following the aforementioned procedure and customized templates. The repaired FRC bridges underwent the same pre-testing procedures, loading, and AE tests. Initial failure loads of the repaired FRC bridges were identified via the conjoined scatter plot from Microsoft Excel.

Data analysis
Both datasets taken from UTM (Force, N) and AE (Energy, µV²) were saved and consolidated with Microsoft Excel (Microsoft Office 2017). The data from either one of the sensors with the higher first energy peak was selected for each sample. After adjusting both data of the same sample to the same time frame (seconds with two decimal points), a scatter plot was mapped to determine the first energy peak which corresponded to the initial failure load and time of initial failure (Fig. 4). All the graphs identifying the initial failure load and time of initial failure were recorded according to the three groups.

All statistical analytical tests were performed using SPSS version 25 (α=0.05). One-way analysis of variance (ANOVA) and posthoc Tukey’s analysis were carried out to detect the differences in the initial failure loading values of the three groups. For the time of initial failure, the Kruskal Wallis test with pairwise comparison was performed. The significant differences between the original and repaired FRC bridges were compared using the paired t-test method. Data for initial failure loads were presented in mean and standard deviation (SD) with a significant level of 0.05 whereas data for time

Fig. 4 Scatter graph plotted for each sample to determine the initial failure load and time of initial failure.
of initial failure was presented in mean rank (seconds) with 0.05 as significance level.

RESULTS

The data of initial failure loading values was normally distributed for each group as assessed by Shapiro-Wilk test ($p>0.05$) and there was homogeneity of variances, as assessed by Levene’s test of homogeneity of variances ($p=0.199$). FRC bridges in CS group (568.56±113.20 N) had the highest initial failure load, followed by AF (447.30±61.38 N), and CR (371.48±92.71 N). One-way ANOVA revealed significant differences between the three groups ($p<0.001$). However, no significant difference was noted between AF and CR ($p=0.173$).

As for the time of initial failures, the data was not normally distributed with Shapiro-Wilk test ($p>0.05$) for all the groups. Kruskal Wallis test revealed statistically significant differences between the three groups ($p<0.001$). Subsequent pairwise comparison showed no significant difference between CS (mean rank 17.90 s) and AF (mean rank 22.0 s) ($p=0.893$). Table 2 shows a summary of the results for both the load and time of initial failure for all three groups. Figure 5 presents the mean and standard deviation of the initial failure loading values between three groups.

Table 2  Summary of the results

<table>
<thead>
<tr>
<th>Group</th>
<th>Sample size, n</th>
<th>Initial failure loads</th>
<th>Time of initial failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean (SD), N</td>
<td>Mean rank (seconds)</td>
</tr>
<tr>
<td>CS</td>
<td>10</td>
<td>568.56 (113.20)$^a$</td>
<td>17.90$^a$</td>
</tr>
<tr>
<td>AF</td>
<td>10</td>
<td>447.30 (61.38)$^b$</td>
<td>22.00$^a$</td>
</tr>
<tr>
<td>CR</td>
<td>10</td>
<td>371.48 (92.71)$^b$</td>
<td>6.60$^b$</td>
</tr>
<tr>
<td>$p$-values</td>
<td></td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Initial failure loads were analyzed using one-way ANOVA. Data presented involve the mean and standard deviation values. Time of initial failure was analyzed using the Kruskal Wallis test. Data are presented in mean rank. A similar letter indicates statistically similar groups.

Table 3  Modes of failures detected in each group

<table>
<thead>
<tr>
<th>Group</th>
<th>Framework fracture</th>
<th>Delamination of composite</th>
<th>Debonding</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>0</td>
<td>6$^*$</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>AF</td>
<td>0</td>
<td>7</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>CR</td>
<td>0</td>
<td>4</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

All modes of failures were recorded according to each group. Framework fracture involves fracture of the FRC bundles. Delamination of composite consists of adhesive failures which exposed the intact FRC framework without involving the connectors. Debonding refers to fracture of composite involving the connectors and/or inlay cavities. Others refer to a combination of failures or catastrophic failures. (*) represents the selected samples for post crack performance test.

Table 4  Results comparing repaired and original FRC bridges with CS framework design

<table>
<thead>
<tr>
<th>Group</th>
<th>Initial failure loads</th>
<th>df</th>
<th>t</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>602.85±137.35</td>
<td>5</td>
<td>4.084</td>
<td>0.01</td>
</tr>
<tr>
<td>Repaired</td>
<td>417.60±46.93</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Differences</td>
<td>185.24±111.11</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Initial failure loads were analyzed using paired t-test. Data presented involve the mean and standard deviation values.
values of the three groups after posthoc analysis.

The modes of failures following the previous literature for each group were recorded in a descriptive table (Table 3). Only samples with the commonest failures seen in the clinical practice from the CS group were selected for the post crack performance test. Data collected were normally distributed with Shapiro-Wilk test ($p=0.949$). The initial failure load of the repaired FRC bridge (417.60±46.93N) was significantly lower compared to those of the original group (602.85±137.35 N) with a $p$-value of 0.01. Table 4 showed the significant differences between original and repaired FRC bridges in mean and standard deviation.

DISCUSSION

In the search for the optimum framework design for a posterior FRC bridge, many researchers proposed a combination approach with multiple FRCs. The latest reviewed design emphasized the principle of cuspal support (CS) during the fabrication of these prostheses. An additional perpendicularly placed reinforced FRC on top of the overall substructure withstands the general masticatory load. The position of the reinforced short FRC should be directly beneath the cusps of the future pontic. The initial failure loading values obtained from a previous study with the same framework design were higher ($\approx$750 N) than the results of the present study (568.56 N). Such outcome could be due to the lack of ageing procedures in the prior research and the different methods of failure identification.

Anatomical-driven framework design instilled the concept of placing multiple FRCs conforming to the anatomy of the pontic. The pontic was usually highly filled with FRCs. However, the quantities and molecular weight of the overall FRC substructure will not be the same as the CS group in this study. For a fair comparison, the modified design (AF) utilized the same amount of FRCs by placing the additional reinforced short FRC in between the two horizontal FRCs. The final effect matched the anatomical outline of a lower 2nd premolar where the middle third of the pontic crown is wider buccolingually with a narrow occlusal table and cervical third. This design also incorporated a U-shaped horizontal FRC which is placed from one cavity to the other. The U-shaped design was previously introduced as a shape optimized substructure design expected to improve the clinical performances of FRC bridges.

The initial failure load of AF was significantly lower than CS by 121.26 N, and the result further confirmed the importance of the cuspal support in resisting the masticatory load regardless of the anatomical features of a pontic.

The circular framework design offered the highest fracture resistance compared with the other designs in the latest in-vitro investigation. Nevertheless, the methodology lacked clarity, and the circular design was not reproducible. To replicate a similar design, the additional reinforced FRC in CR group was stretched out by finger pressure against an oil paper and parallely placed to circulate the two horizontal FRCs completely. Unlike the outcome in the previous study which indicated no significant differences between CS and CR, the CR group underperformed relative to the other two groups in this investigation. The lack of cuspal support and the parallel placement of the circular reinforcement could have contributed to the early failure. This finding was in accordance with that of another research in which the perpendicular placement of the additional support could withstand the highest load.

Furthermore, the mean initial failure loads for the framework designs AF and CR were below the estimated masticatory load of 500 N posteriorly after ageing. FRC bridges with these designs could have begun to fail within the natural chewing forces, and those with CR framework design failed at the earliest. The FRC bridges with CS framework design can withstand the masticatory load, provided that the additional FRC cuspal support was placed perpendicularly and directly against the opposing tooth.

Post crack performance further demonstrates the efficiency of the framework design in the fabrication of a posterior FRC bridge. The context of the composite repair is seldom studied in FRC bridges. Thus, a simple and clinically applicable repair protocol was proposed in this study. The micromechanical features of the fractured FRC were enhanced with surface roughening via diamond burs. Air abrasion is the recommended technique for preparing the composite surface for repair, but it may be inappropriate in FRCs due to the micro-irregularities formed on the glass fibers. The long-term effect of the embedding aluminum oxide particles is also not well understood. Composite surfaces treated with fine-grit diamond burs have an intermediate surface roughness which offers the highest repair bond strength. Furthermore, diamond burs are readily available in any clinical armamentarium, and additional clinical skill is not required to perform this procedure.

Another consideration for a successful repair is the chemical attachment between the aged FRC surfaces and the newly placed composite. To date, various materials such as silane coupling agents and IMR were explored but no available. To implement a simplified approach for the repair protocol, IMR was used in this study because of its ability to reactivate the FRC substrate. Notwithstanding the previous research on high potential in repairability, significant differences were found between the initial failure loads of the repaired and the original FRC bridges. In their investigation, the FRC failing surfaces were simulated solely by removing the oxygen inhibition layer (OIL) over blocks of specimens. By contrast, the fracture composite in this study was derived from the mechanically loaded FRC bridges which resembled the actual clinical scenario. The photo-initiator system from StickResin could impede the dissolution ability of Bis-GMA and lowered the tensile bond strength of the adhesive interface. Another contributory factor for the different results is the presence of a thick OIL on roughened FRC surfaces.
The high surface irregularities of FRC tend to retain thicker OIL, thereby resulting in decreased repair bond strength.\(^{26}\)

The long reactivation time (5 min) from the IMR may be one of the shortcomings if such chemical reacting solution was used intraorally. Another chemically induced bonding used frequently in dentistry is silane solution was used intraorally. Another chemically induced bonding used frequently in dentistry is silane solution, which was claimed as the optimum silane coupling agent and it was considered as the optimum method of surface treatment along with silane coupling agent present. Particularly in E-glass FRCs, silane coupling agent enhances the bonding between the inorganic substances in the other end. The activation of silane coupling agent takes roughly 30–60 s depending on the manufacturers. Particularly in E-glass FRCs, silane coupling agent enhances the bonding between the un polymerized composite matrix in one end and the inorganic component in the other end. The activation of silane coupling agent is necessary to perform surface treatments of the restorative materials to activate the substrate surface for stable linkage with composite resin.\(^{25}\) The various methods of surface treatment along with silane coupling agent seem promising but the application in repair FRC bridges may warrant future investigations especially in reducing the chairside time.

An improved methodology was imposed in this study by instilling the presence of a PDL in the prepared specimens. The elastic properties of the elastomeric silicone material can achieve 92% of the recovery phase, an outcome similar to the values obtained in a healthy natural PDL.\(^{26}\) Besides coating the roots with a thin layer of silicone material, the spacing between the root surface and the simulated acrylic socket also played a role in the final deflection of the tooth. The geometry of the roots for all laboratory specimens should have standardized shapes and sizes so as to accurately present the same class of tooth mobility.\(^{27}\) Therefore, the root surfaces of all the specimens in the study were prepared with a composite built up via a customized transparent silicone template. Furthermore, the loads were placed at the buccal cusps of the pontic to replicate the actual occluding forces. Multiple articles indicated that significant differences were found between occlusal and buccally placed loads.\(^{5,18}\) Results obtained from the load placed at the central fossa tend to show catastrophic fractures, whereas loading on the buccal cusps only produced cracks and delamination (the most common types of failure observed clinically).

Limitations of the study should be considered in future experiments to improve the clinical relevance of these findings. Dynamic loads can be performed to simulate chewing forces so the crack propagation of such prosthesis can be investigated. Time discrepancy calculated from two sensors may suggest the location of the initial failures provided that the cavity sizes are standardized. Upcoming studies may include identifying the specific sites of initial failures within the FRC bridges which can be useful in the fabrication of such a prosthesis. Besides, the abutment teeth were generally collected and prepared in an ideal condition without saliva contamination, hence, decontamination procedure was not introduced prior to repair protocol. As for the techniques of FRC repair, more sophisticated repairing methods should be introduced with specific exploration on the aged FRC surfaces after loading failure.

**CONCLUSION**

Framework design with a perpendicularly placed additional FRC reinforcement for cuspal support is crucial in fabricating a successful posterior FRC bridge. However, these prostheses with the optimum framework design may have limited potential in terms of repairability, and further investigation in this context should be performed.

**CONFLICTS OF INTEREST**

The authors declare no conflict of interest.

**REFERENCES**