Effect of Intermediate Fiber Layer on the Fracture Load and Failure Mode of Maxillary Incisors Restored with Laminate Veneers

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This study evaluated the fracture load and failure mode of various veneer materials cemented with or without the addition of a fiber-reinforced composite (FRC) layer at the adhesive interface. Sixty intact incisors were randomly divided into three groups. Group 1 was fabricated with the heat-press technique (IPS Empress 2); Group 2 with the copy milling technique (ZirkonZahn); and Group 3 with the direct or indirect composite technique (Z250) — and specimens were cemented either with or without FRC at the adhesive interface. The specimens were thermocycled and tested with a universal testing machine. No significant differences in fracture load (p>0.05) were found among the various veneer materials. The addition of FRC at the adhesive layer did not lead to significant differences in the fracture load (p>0.05) but resulted in differences in the failure mode. Laminate veneers made of composite, zirconia, and Empress 2 showed comparable mean fracture loads. However, the use of FRC at the interface changed their failure modes.

Keywords: Laminate veneer, Fiber-reinforced composite, Load-bearing capacity

INTRODUCTION

The restorative treatment of discolored, malpositioned or fractured anterior teeth is still a challenge for dental practitioners. Full crowns provide very satisfactory results, but the loss of sound tooth structure is regarded as an important drawback12. The development of adhesive techniques has increased the use of ceramic or particulate filler composite (PFC) veneers as minimally invasive treatment options. Compared to traditional full preparation restorations, minimal reduction of tooth structure, good esthetic properties, color stability, and reliable bonding are the major upperhand advantages of laminate veneers and they are indeed a welcoming change4,5. Addressing the practical concerns, the longevity of porcelain veneers has been clinically evaluated and shown to range from 3 to 15 years611. Despite the advantages, dental practitioners are still cautious when considering ceramic laminate veneers. This is chiefly because their fractures account for 67% of the total failures. Incisal chippings and development of cracks are the most common reasons for clinical failures of ceramic veneers6,1113. These failures arose due to the brittle nature of ceramics and their inability to accommodate tensile forces by plastic deformation11.

Today, stronger and tougher ceramic materials are available, such as Empress 2 (Ivoclar, Vivadent) — a lithium disilicate-reinforced glass ceramic, or Ice Zirkon — a partially yttrium-stabilized zirconium dioxide (Ice Zirkon, ZirkonZahn). The flexural strength of lithium disilicate-reinforced glass ceramic ranges from 300 to 400 MPa15, whereas that of zirconia ranges from 680 to 1140 MPa16.

Alternatively, direct or indirect use of PFC provides the advantages of relatively low cost, inherently less brittleness compared to ceramics, and reliable bonding properties. However, they seem to be plagued and limited by low mechanical properties17. Fiber-reinforced composites (FRCs), on the other hand, have been used to increase the mechanical properties of composite restorations without compromising the esthetic properties18,19. They have been shown to have the ability to withstand tensile stresses and stop crack propagation at the adhesive interfaces20,22. However, limited research has been done on the use of FRC in esthetic laminate veneers20.

Therefore, it was the purpose of this in vitro study to examine the fracture load of laminate veneers fabricated with different restorative materials, as well as their failure modes by virtue of FRC addition at the adhesive interface. The null hypothesis to be tested was that there is no difference in the fracture load and failure mode among the various laminate veneer materials and that the addition of FRC makes no difference in the fracture load or failure mode of laminate veneers.
MATERIALS AND METHODS

Sixty, caries-free human maxillary central incisors with similar dimensions — which were extracted for periodontal reasons — were randomly selected for this study. The teeth were stored for a maximum of three months in 0.5% chloramine solution prior to use. Adhering soft tissues and calculus deposits were removed with a hand scaler, and the buccal-palatal, mesio-distal, and cervico-incisal dimensions of each tooth were measured with a digital micrometer (Mitutoyo Corp., Tokyo, Japan; accuracy of ±0.002 mm). The teeth were mounted in a cylindrical block (2.5 cm diameter), 2 mm below the cementoenamel junction, using a self-cure acrylic resin (Palapress, Heraeus Kulzer, Germany). The teeth were then divided into three groups (n=20), and each group was assigned to a different fabrication technique: Group 1 (EMP), heat-press technique (IPS Empress 2, Ivoclar Vivadent, Schaan, Liechtenstein); Group 2 (ZRC), copy milling technique (Zirkonzahn, Bruneck, Italy); and Group 3, direct (PFc) or indirect (IPFC) composite veneering technique (Filtek Z250, 3M ESPE, USA). All teeth were stored in Grade 3 deionized water except when the experimental procedure required moisture isolation.

Tooth preparation

Prior to tooth preparation, a sectional index that could be reconstructed over the original tooth was produced using a polyvinylsiloxane impression material (Elite H-D, Zhermack, Germany). The teeth were prepared using freehand technique by a single clinician. Further, to avoid biases caused by the degree of repetition, the teeth were prepared on three different days at different intervals.

During preparation, depth of the removed tooth structure was controlled with the polyvinylsiloxane index. The facial and palatal surfaces were reduced to 0.5—1.0 mm and incisal reduction was 1.5 mm. All the incisors were prepared with a chamfered finishing line with rounded internal line angles. The cervical preparation ended at the cementoenamel junction. Smooth margins were created to prevent stress concentration zones. Once the preparation was completed, impressions were made for all groups — except the direct laminates — using polyvinylsiloxane impression material (Elite H-D, Zhermack, Germany), and cast in vacuum-mixed Type IV dental die stone (Fujirock, GC Corp., Tokya, Japan) according to the manufacturer’s recommendations. Stone dies were carefully separated from the impressions and two coats of die spacer (Die Spacer Tray, Kerr) were applied 0.5 mm short of

<table>
<thead>
<tr>
<th>Product</th>
<th>Type</th>
<th>Lot no.</th>
<th>Manufacturer</th>
<th>Material composition</th>
</tr>
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<tr>
<td>Vococid</td>
<td>Etching agent</td>
<td>590722</td>
<td>Voco GmbH, Cuxhaven, Germany</td>
<td>35% orthophosphoric acid</td>
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<tr>
<td>Solobond plus primer</td>
<td>Primer</td>
<td>591582</td>
<td>Voco GmbH, Cuxhaven, Germany</td>
<td>Maleic acid, hydrophilic methacrylates, polyfunctional monomers, acetone, water</td>
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<tr>
<td>Solobond plus adhesive</td>
<td>Bonding agent</td>
<td>591583</td>
<td>Voco, Cuxhaven, Germany</td>
<td>HEMA, polyfunctional monomers</td>
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<td>Filtek Z250</td>
<td>Hybrid composite resin</td>
<td>6021A3,5</td>
<td>3M ESPE, St Paul, MN,USA</td>
<td>Bis-GMA, UDMA, Bis-EMA, 60 vol% fillers</td>
</tr>
<tr>
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<td>Unfilled resin</td>
<td>5509986</td>
<td>Stick Tech. Ltd., Turku, Finland</td>
<td>Bis-GMA, TEGDMA</td>
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<tr>
<td>StickNet</td>
<td>Porous polymer preimpregnated bidirectional FRC</td>
<td>2020218-W-0042</td>
<td>Stick Tech. Ltd., Turku, Finland</td>
<td>Porous PMMA, E-Glass fibers: 0.06 mm thickness</td>
</tr>
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<td>Dual cure resin luting agent</td>
<td>530324</td>
<td>Voco, Cuxhaven, Germany</td>
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<td>Ultradent porcelain etch</td>
<td>Etching agent</td>
<td>026</td>
<td>Ultradent Inc., USA</td>
<td>9% Hydrofluoric acid</td>
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<tr>
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<td>Silane</td>
<td>580382</td>
<td>Voco, Cuxhaven, Germany</td>
<td>MPS, alcohol and water</td>
</tr>
</tbody>
</table>

Bis-GMA: Bisphenol-A-glycidyl dimethacrylate; TEGDMA: Triethylene glycol dimethacrylate; UDMA: Urethane dimethacrylate; Bis-EMA: Bisphenol A polyethylene glycol diether dimethacrylate; PMMA: Polymethyl methacrylate; HEMA: Hydroxyethyl methacrylate; FRC: fiber-reinforced composite; E-glass: E-glass fibers, silanated; MPS: 3-methacryloxypropyl trimethoxysilane
the finish line of the preparations.

**Preparation of the laminate veneer restorations**

Table 1 lists the manufacturers’ information, lot numbers, compositions of etching agent, bonding agent, PFC and FRC materials used in this study. Laminate veneers were fabricated with a standardized thickness using the impression molds made before tooth preparation.

**Group 1 (EMP) (lithium disilicate-reinforced glass ceramic):** 20 veneers were waxed to duplicate the original form using the polyvinylsiloxane index and spruced. The veneers were fabricated from lithium disilicate-reinforced glass ceramic material, IPS Empress 2, using the heat-press technique according to the manufacturer’s recommendations. After divestment, the veneers were finished and glazed.

**Group 2 (ZRC) (partially yttrium-stabilized zirconium dioxide):** Indirect laminates were fabricated using PFC (Filtek Z250) on the dies with the guidance of the polyvinylsiloxane index, and the veneers were fabricated with the copy milling technique using zirconium oxide blocks (ICE Zirkon, ZirkonZahn, Italy) according to the manufacturer’s recommendations.

**Group 3 (particulate filler composite):** The PFC laminates were divided into two subgroups according to the fabrication technique as direct and indirectly prepared particulate filler composite.

**Direct particulate filler composite (PFC):** Each tooth was etched for 15 seconds using a 35% phosphoric acid etching gel (Voccid, Voco). Subsequently, the tooth surface was rinsed thoroughly and air-dried gently. Dentin primer and adhesive were applied according to the manufacturer’s instructions (Solobond plus, Voco). Following the bonding agent application, a layer of FRC (0.06 mm) was applied to the surface and light-polymerized for 40 seconds (Elipar Free Light, 3M ESPE) at 740

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Fig. 1 Schematic illustration showing the preparation steps of different laminate restorations. EMP: Empress 2, ZRC: zirconia, PFC: particulate filler composite, IPFC: Indirect particulate filler composite.
mW/cm² light intensity. PFC laminate was built up in two increments and 40 seconds’ light irradiation was used for every increment. After application of the fiber layer, the tooth surface was restored with PFC (Filtek Z250, 3M ESPE). To duplicate the original configuration, the polyvinylsiloxane index was sectioned axially along the midline in order to enable build-up of the restoration in layers, and PFC was injected.

**Indirect particulate filler composite (IPFC):** The indirect PFC veneers (Filtek Z250) were fabricated with the same technique using the polyvinylsiloxane index on the dies. In addition to light polymerization, they were further polymerized in a light-curing oven (LicoLite, Dentsply De Trey GmbH, Dreieich, Germany) for 15 minutes in which the temperature rose to ca. 80°C.

**Cementation**

Dual-cure resin luting agent (Bifix, Voco, Germany) was used for the cementation of the laboratory-made laminate veneers. The etching, bonding, and priming steps followed the same procedure as in direct restoration group. After etching, the dentin surfaces were dried gently to maintain the shiny and visibly hydrated surface.

The inner surfaces of indirect veneers were treated with air particle abrasion using 50 μm Al₂O₃ (Korox, Bego, Germany). For this purpose, a chairside air abrasion device (Cobet, 3M ESPE, Germany) was used from a distance of 10 mm at a pressure of 250 kPa bar for 10 seconds. Each surface treatment was followed by silanization. A silane coupling agent (Ceramic Bond, Voco) was applied to the internal veneer surface for 60 seconds and air-dried. In addition to air particle abrasion treatment, Group 1 was acid-etched with 9% hydrofluoric acid prior to silanization.

Subsequently, Groups 1 and 2 were divided into two subgroups according to the interface layer. Before cementation, one group (EMP-FRC or ZRC-FRC) received a layer of porous, polymer-preimpregnated, bidirectional FRC at the cementation interface (thickness per layer: 0.06 mm) (StickNet, Stick Tech.), whereas the other group (EMP or ZRC) received no FRC (Fig. 1). Before application, the FRC layer was cut and adapted to 0.5 mm short of the finish line of the preparations. Then, the FRC layer was further impregnated with a light-curing adhesive resin (Stick Resin, Stick Tech.) for one hour in a dark container. The further impregnation of the polymer-preimpregnated fibers with a light-curing resin matrix formed a semi-interpenetrating polymer network of relatively coarse structure. This structure was previously shown to boost the bonding strength. After further impregnation, the FRC layer was applied to the prepared tooth surface. After which, the veneers were gently seated on the abutment teeth and excess cement was removed with microbrushes and light-cured from palatal, facial, and incisal sides for 40 seconds. The margins were finished with polishing disks (Sof-Lex, 3M ESPE). Cementation of the groups without FRC followed the same procedure.

The specimens were first stored in water at 37°C for 24 hours and then subjected to thermocycling in Grade 3 deionized water for 6000 cycles between 5°C and 55°C, with a dwell time of 30 seconds and a transfer time of five seconds. At 24 hours after thermocycling, a load test was performed using a universal testing machine (Lloyd LRX, Lloyd Instruments Ltd., Fareham, UK) at a crosshead speed of 1.0 mm/min. To simulate the clinical situation as closely as possible, the teeth were loaded from the incisal direction with a 135-degree inclination (Fig. 2). Load deflection curve was recorded with a Nexygen 4.0 software (Lloyd Instruments Ltd.). The teeth were stored in water except for the testing period.

The fracture pattern of each loaded specimen was observed visually and with a stereomicroscope (Wild M3B, Heerbrugg, Switzerland). Failure modes were classified as follows: cervical fracture of the tooth, cohesive tooth fracture extending below the cementoenamel level, adhesive failure between the laminate and tooth, and mixed failure of partly adhesive and partly cohesive failures between tooth and laminate veneer including fractures extending to less than 1/3 of the tooth structure, or cohesive laminate failure including chipping and small fractures limited to the laminate only.

Data for all the groups were analyzed statistically with factorial analysis of variance (ANOVA). This was followed by Tukey’s post hoc test at a significance level of p<0.05 using SPSS 14.0 software (Statistical Package for the Social Science, SPSS Inc., Chicago, Illinois, USA) to establish the effects of
laminate veneer material and fiber layer.

RESULTS

Figure 3 shows the mean fracture loads and standard deviations. Although some groups had higher fracture loads, ANOVA showed no significant differences among the different laminate veneer materials (p>0.05). The use of bidirectional FRC at the cementation interface did not change the fracture load significantly (p>0.05) when compared with the groups without FRC at the interface. Among the test groups, the lowest mean fracture load was obtained for Group 1 veneers with a FRC layer at the interface (EMP-FRC) (552.2 N), whereas the highest was obtained for the indirectly made composite laminate veneer with FRC at the interface (796.1 N).

Table 2 shows the failure modes of the different groups. In Group 1 without the FRC layer, 50% of the fractures were adhesive failure between the tooth and veneer. Cervical tooth fracture (30%) and cohesive fracture of the laminate veneer (20%) were also observed. With the addition of the FRC layer, cervical fracture increased to 50%. Cohesive failure in the laminate was also observed. The fractured parts were totally detached from the tooth surface showing splitting of the FRC layer.

In Group 2 without a FRC layer, all the specimens showed cervical tooth fracture (100%). However, with the addition of a FRC layer, cervical fracture decreased to 50%. Further, cohesive fracture inside the tooth structure (20%), adhesive-cohesive mixed failure (20%), and adhesive failure (10%) were observed. The fractured laminates were totally detached from the surface, leaving the FRC layer attached to the tooth surface.

In Group 3 for directly made PFC laminate veneers, there was chippping of the PFC together with partial splitting in the FRC or partial exposure of the FRC layer (70%), as well as 20% cervical tooth fracture. For the veneers which showed splitting in the FRC layer, they were still partly attached to the tooth surface. Indirectly made PFC laminates showed more cervical tooth fractures (50%). Besides, adhesive failure between the tooth and laminate veneer (20%) and cohesive failure within the veneer were also observed. As for cohesive failure within the veneer, it entailed partial splitting in the FRC layer with the laminates still attached to the surface after failure.

DISCUSSION

The relentless pace of innovation and development in restorative materials and techniques culminates in offering clinicians a whole plethora of esthetic materials with different mechanical properties — and at different costs. Therefore, this in vitro study was designed to compare the load-bearing capacity of central incisors restored with different laminate veneer materials.

Tooth preparation is known as one of the most critical steps in the use of laminate veneers. The freehand technique was used for the laminate veneer preparation, as it is a typical technique in clinical practice. A polyvinylsiloxane index was used to control the preparation depth for each tooth. Laminate veneer preparations were recommended to be restricted to enamel²⁰. However, especially in areas where the enamel is thin, dentin exposure is possible. On this account, a standardized three-step etching, priming and bonding approach was used for all the groups.

Laminate veneers are subjected to continuous functional loading in the oral cavity. The loading of the veneer-tooth system at the incisal edge in a
direction parallel or perpendicular to the long axis of the tooth is a common approach in testing the load-bearing capacity of different restorations\textsuperscript{22,26}. However, in clinical conditions, the stresses that affect the maxillary incisors during mastication are not directed to the long axis of the tooth. Therefore, an inclined loading condition was used in this \textit{in vitro} study to simulate the clinical situation as closely as possible.

The authors hypothesized that there would not be any significant difference in load-bearing capacity or fracture mode among the different materials. Within the limitations of this \textit{in vitro} study, the hypothesis was not fully rejected. Although the mean failure load values were not statistically different among the different restorative materials, the failure modes were different. Despite the known mechanical differences in the properties of the materials, they all produced a strong structure when they were bonded to the tooth structure. In particular, the mean failure loads of the groups in this \textit{in vitro} study ranged from 552 to 796 N, reaching levels higher than the physiological biting force of the anterior teeth which somewhat varies between 108 and 176 N\textsuperscript{26}.

Concerning mechanical properties, zirconia has a much higher strength compared to the other materials\textsuperscript{15,16}. However, the failure load of ZRC group was lower compared to the indirect composite group. The high elastic modulus of zirconia, compared to dentin or enamel, might not be optimum for the load-bearing capacity of the resultant structure. On the contrary, the indirect PFC material — supported by a FRC layer — has an elastic modulus around 12–18 GPa\textsuperscript{27}, which is close to that of dentin (10–20 GPa)\textsuperscript{28}. Consequently, this might have resulted in a more homogeneous stress distribution, thereby leading to a higher mean failure load of the tooth-laminate structure.

Between the two composite laminate groups, the indirect composite laminate group showed a higher mean failure load compared to the direct group. The higher fracture strength obtained with the indirect PFC veneer was consistent with a previous research showing an increased degree of conversion and an increase in mechanical properties with post-cured PFC materials\textsuperscript{29}. However, the high fracture loads obtained with the use of PFC was partially in conflict with a previous study\textsuperscript{23} that showed significantly higher fracture strength values for direct composite laminate veneers compared to indirect ones. Compared to the previous report\textsuperscript{29}, higher fracture loads obtained with both direct and indirect PFC in this study might arise from the different PFCs used in both studies and the matrices of the FRC materials used as reinforcement.

A composite resin containing four-functional urethane methacrylate might have higher cross-link density\textsuperscript{30}, which might result in a more brittle composite compared to the one used in the current study. On the other hand, the porous, polymer-preimpregnated FRC which was employed in this study consisted of a coarser structure of originally micrometer-scale porous PMMA that was used in the preimpregnation of fibers. It is noteworthy that this structure has well-documented bonding properties through interdiffusion bonding\textsuperscript{21,30}. Additionally, the indirect restorations were air-abraded and silanized before cementation. It is also noteworthy that the combined effect of air abrasion and silanization was previously shown to increase the bonding reliability between PFC and FRC layer\textsuperscript{31}. Taken together, a slightly higher fracture strength was thus obtained with indirect veneers as compared to the direct ones in this study. Furthermore, the low percentage of adhesive failure (20\%) observed for the indirect PFC group supported this suggestion.

In addition to functional loads, a laminate veneer-tooth complex is also subjected to polymerization shrinkage of the luting cement and temperature changes in the oral environment. Dental ceramics are susceptible to slow crack growth at the crack tip of surface flaws exposed to a moist environment as a result of the hydrolysis of silicate bonds\textsuperscript{32}. It has been previously reported that surface flaws may extend as a consequence of stresses induced by thermal variations in ingested foods and drinks. Therefore, postoperative cracking and resultant failure of laminate veneer restorations are considered to be possible consequences of thermal variations and polymerization shrinkage\textsuperscript{33}. On this ground, thermocycling before fracture load testing was used as an aging method in this study.

Previous research on veneer repairs has shown the beneficial effects of bidirectional FRC on interfacial strength and crack propagation\textsuperscript{20,22}. The addition of fibers close to the preparation surface was expected to reinforce the weakened tooth structure and distribute stresses evenly, to the end of avoiding detrimental stress concentrations at the cervical and incisal sites\textsuperscript{39} of the laminate veneer. Results of the present study, however, did not show any significant increase in the fracture load of the tested laminate veneers with the addition of a fiber layer. On the other hand, as per a previous research, a change in failure mode was observed. Furthermore, the preparation design in the present study differed from those of previous studies where retentive preparation designs were used. Reinforcing the retentive parts of the veneer by FRC could have provided even higher load bearing values\textsuperscript{39}.

Failure analysis of the fractured laminates showed different types of failures for different materials. Out of 60 restored specimens, about 30 (50\%)
showed cervical failure in the natural tooth structure without involvement of the laminate veneer restoration. In particular, the failure mode for ZRC was 100% cervical tooth fracture. This might be related to the increased stiffness of the tooth and ZRC laminate structure, causing stress concentration in the cervical area. The cervical fractures of incisors under static loading conditions are a common observation, as reported in other previous studies. The ZRC veneers were mostly intact after testing, suggesting that they were able to resist the stresses transmitted from the failing tooth structure to the restoration. When the stresses exceeded the limit of the tooth structure, the tooth failed first.

When a layer of FRC was applied, cervical fractures were decreased by about 50% for the ZRC group, leaving the layer of FRC on the tooth surface. Bidirectional FRC has previously been shown to have good bonding with dentin. With a good bonding, the bidirectional FRC can reinforce the tooth interface in two directions, distributing the stresses more evenly and increasing toughness by preventing crack propagation. This might then change the stress distribution pattern and lead to higher stress concentrations between the ZRC and FRC layers, resulting in a decrease in cervical fractures and an increase in adhesive-cohesive laminate failures. Although silane treatments were previously shown to improve the bonding with zirconia, bond strength was reported to decrease after thermocycling. In the present study, the possible bond failure after thermocycling between zirconia and FRC, coupled with changes in the interface dynamics due to the addition of fibers, might be the reason for the decrease in cervical fractures for the ZRC group and also for the relatively low load-bearing capacity.

On the contrary, bonding to Empress is known to be good following HF acid with silane treatment. Therefore, a relatively good bonding was expected between Empress and FRC. Verily, the failure analysis results confirmed this assumption as the FRC layer was attached to both the tooth structure and partly to the Empress veneer. Young’s modulus of lithium disilicate-reinforced glass ceramic was previously reported to be 105 GPa, whereas that of partially yttrium-stabilized zirconium dioxide was 240 GPa. As Empress was more brittle by nature compared to zirconia, the addition of FRC as an intermediate layer might have increased the stiffness of the tooth-laminate structure, resulting in the failure of the brittle Empress laminate.

As for the chipping-type failures observed in direct and indirect PFC laminates, they might be related to the effect of the PFC layer. The FRC layer was stiffer than PFC, and thus was possibly able to slow crack propagation, resulting in chipping, or delamination of the overlying PFC layer. However, in both the direct and indirect PFC groups after failure, the laminates remained attached to the surface, thereby confirming the good bonding between FRC-PFC and FRC-tooth surface.

Within the limitations of this study, it could be concluded that the various materials used for laminate veneers showed comparable fracture strength. The addition of FRC at the interface showed no effect on fracture strength but resulted in changes in the failure mode. Further investigation is thus needed to elucidate the precise fracture mechanics at the interface.

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REFERENCES

9. Dunne SM, Millar BJ. A longitudinal study of the


