INTRODUCTION
The increasing popularity and widespread use of fiber posts is inevitably changing the endodontically treated tooth reconstruction procedure. The major advantage of fiber posts is their similar elastic modulus to dentine, producing a stress field similar to that of natural teeth. Metal posts exhibit high stress concentrations at the post-dentine interface. Clinical studies have reported that using a fiber post could reduce the incidence of root fractures and the most common cause of failure becomes debonding. Debonding is more likely to occur in the absence of the desirable “ferrule effect”, or in the presence of an excessively thick layer of cement because there is a high prevalence of oval shaped canals in human dentition, even in the apical region. Canals are prepared to preserve the morphology as far as possible to receive a post to adapt to the root canal anatomy as produced by endodontic treatment.

In recent years translucent and radiopaque fiber posts have been achieved. However, the evolution of fiber post shapes are only include a double cylinder designed for retention purposes, cylindrical (Endopost) and simplified oval (conical) profiles (DT posts), based on the good performances of the new bonding procedures. A controversy still remains as to whether anatomical posts adapt better than circular posts to the oval canal morphology. Some studies pointed out that the resin cement thickness was significantly lower in the anatomical post group than in the control standardized posts with good anatomical posts adaptation evident.

However, another study implied that oval posts do not adapt better than circular posts to the oval canal morphology.

Today’s fiber posts usually contain a high volume of continuous (long) reinforced glass fibers embedded in a polymer matrix, which keeps the fibers together and extruded through a preformed cast to form cylindrical/oval (conical) profiles. Anatomical post using short glass fibers reinforced with different cross-sections and slot/grooves enhance retentions can be manufactured by using precise injection molding. However, the inherent mechanical behaviors of the flexural strength and flexural modulus components for this low volume percentage of short glass fiber reinforced posts are warranted. Simulating the failure process of post/core/crown restorations to receive the repetitive (fatigue) and the multi-vectorial nature of inter-oral (rotational and lateral loads) forces must be evaluated.

The objective of this study was therefore to develop a novel anatomical post containing short glass fiber reinforced (anatomical SGFR) with slot/notch retention designs manufactured using precise injection molding. The novel anatomical SGFR fiber post is evaluated and compared to commercial cylindrical continuous fiber post of flexural strength/flexural modulus using the three-point bending test and rotational/lateral fracture resistance on crown/core restorations in artificial acrylic teeth under static/fatigue tests.

MATERIALS AND METHODS
Anatomical SGFR fiber post design and manufacture
The total length of this post is 17 mm included contained...
tip (6 mm), middle (6 mm) and coronal (5 mm) regions. Corresponding three cross-sections in the fiber post were designed in circular shape (radius: r1 is 1.0 mm) at the tip region to fit well with the tooth root apical, circular-oval shape (radius from r1 changed to r2, r2 is 1.6 mm) at the middle region and oval shape (major axis: a=2r2; minor axis: b=r2) at the coronal region to fit well the tooth anatomical oval shape. Surface slots with 0.25 mm radius surrounding the post and four transverse notches with 0.7 mm pitch were designed to increase the contact areas between the post and cement to enhance the post, cement and core retention (Fig. 1(a)).

The anatomical SGFR fiber post material “GRIVORY GVX-7H natural” (EMS-CHEMIE Holding AG, Herrliberg, Switzerland) was supplied as in granulate based on semi-crystalline polyamides and the SGFR fiber post was manufactured using an injection-molding machine (Polypax, Green Point Enterprise, Taichung, Taiwan). Granulated of thermoplastic plastic (GVX-7H) was fed from a hopper into the injection molding machine with 270°C polymer and was forced under high pressure (150 bar) into a mold cavity through an opening valve. The molding was warmed before injecting and the plastic was injected quickly to prevent it from hardening (speed 0.77 s, 56 bar, 270°C) and pressure was maintained for a short time (0.5 s, 50 bar) to prevent the material creeping during setting (hardening). The mold was equipped with a cooling system providing controlled cooling and solidification of the material (cooling time 20 s). The polymer was held in the mold until solidification and then the mold opens to complete SGFR post prototyping. The density of anatomical SGFR post material “GRIVORY GVX-7H natural” (EMS-CHEMIE Holding AG) is 1.85 g/cm³ and supplied as in granulate based on semi-crystalline polyamides. It is a 70% glass-fiber reinforced engineering thermoplastic material with 0.8–1.0 mm length based on a combination of semi-crystalline polyamide matrix with partially aromatic copolyamide. The volume of one anatomical SGFR post is 24.56 mm³ calculated from CAD package and its corresponding mass is 6.7e-3 g measured by electronic balance (Shimadzu TX223L, SHIMADZU, Kyoto, Japan). Therefore, the fiber volume of this material is 6.7e-3 g*70%(1.85*10-3)=2.535 mm³. Comparison of detailed information of a laboratory fiber post and commercial fiber post were indicated in Table 1 and the sectional photographs of a laboratory fiber post was showed in Fig. 1(a). The profile comparison between our new novel anatomical SGFR fiber post and the commercial X-Post is shown in Fig. 1(b).

Mechanical three-point bending test of posts
The three-point bending test was used according to the ISO 10477 standard to measure the flexural strength and modulus of our anatomical SGFR and X-Post. The SGFR-post was placed on the jig horizontal (span length was 10 mm) and aligned the middle of the post with the tip of the load device. The load was applied on the post till the fracture occur and recorded the fracture position. The cross-sectional area of all posts were oval shape and the calculating formula was modified to obtain the Flexural strength (δf) and flexural modulus (E). Flexural strength (δf) and flexural modulus (E) were calculated from the following formulas:

Circular-shaped cylinder: \( \delta_f = \frac{8F_{\text{max}}l}{\pi d^3} \quad E_f = \frac{4S l^3}{3\pi d^3} \)

Fig. 1  (a) Schematic of an anatomical SGFR fiber post design contained three different cross-sections (circular/circular-oval/oval) and combined slot/notch retention designs. (b) Schematics of anatomical SGFR and commercial fiber post inserted in an endodontically treated premolar.
Table 1  Comparison of detailed information of a laboratory fiber post and commercial fiber post

<table>
<thead>
<tr>
<th>Fiber volume / Density</th>
<th>Type of glass fiber</th>
<th>Length of fiber</th>
<th>Composition of the matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGFR-Post</td>
<td>70%(w/w) / 1.85 g/cm³</td>
<td>E-Glass Fiber</td>
<td>0.8–1.0 mm (Short fiber)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Semi-crystalline Polyamide with partially aromatic copolyamide (70%)</td>
</tr>
<tr>
<td>X-Post Radix Fiber Post</td>
<td>76.2%(w/w)*</td>
<td>Zirconium-enriched glass fiber (60%)³¹</td>
<td>200 mm (Long fiber)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Epoxy resin (40%)³¹</td>
</tr>
</tbody>
</table>

*Custom test by FTIR (Fourier transform infrared spectroscopy) & TGA (Thermogravimetric Analysis) technique from Plastic Industry Development Center, Taichung, Taiwan.

Oval-shaped cylinder: \( \delta = \frac{8F_{\text{max}}l}{\pi2ab} \)  
\[ E_s = \frac{4Sl^3}{3\pi a b} \]

where \( F_{\text{max}} \) is the applied load (N) at the highest point of load-deflection curve, \( l \) is the span length (10.0 mm), \( d \) is the diameter of the circular specimen. The formulas for oval-shaped cylinder were derivation from circular-shaped cylinder, where \( a \) and \( b \) are lengths of major and minor axis in the oval specimen. \( S \) (stiffness) = \( F/D \); the stiffness (N/m) and \( D \) is the deflection corresponding to load \( F \) at a point in the straight line portion of the trace.

Artificial endodontically treated premolar preparation
In order to reduce the variation for a large amount of natural teeth, a freshly extracted intact maxillary upper second premolar was scanned with micro-CT (Skyscan, Aartselaar, Belgium) to generate solid CAD program models (ProEngineer Wildfire 5, Parametric Technology, Needham, MA, USA). The dimension of the remaining dentin was defined to 15 mm in total length, containing a ferrule design 2.5 mm in height, 1.5 mm in width and 1.3 mm diameter with a root canal 3 mm in height (Fig. 1(b)). The solid dentin model can be milled to duplicate the artificial acrylic dentin (Regular Transparent-BX-001, NAN-YA Plastic, Taipei, Taiwan) (Fig. 1(b)) and was embedded from the root to 1.5 mm below the CEJ into a simplified bone block with epoxy resin material containing an inner socket cut from the dentin outer profile.

The artificial tooth was cleaned using an ultrasonic system and then washed in water for 30 s. The total length of our anatomical SGFR and commercial fiber posts (X-Post Radix Fiber Post No. 1, Dentsply Maillefer, Ballaigues, Switzerland) was 13 mm and inserted into the root canal according to clinical treatment procedures. A preformed milled aluminum crown (butterfly-shaped) and composite core (Core-x-flow, Dentsply Maillefer) were then luted using RelyX U200 cement (3M ESPE, Seefeld, Germany). Fifty-two samples were prepared and separated into two groups, 16 and 36 samples were arranged for the following rotational static/dynamic and lateral static/fatigue resistance tests, respectively.

Static and cyclic rotational resistance tests
Sixteen butterfly-shaped crown sampled were randomly arranged into two groups, anatomical SGFR fiber post and X-Post for the rotational resistance tests using the SE MODEL 2205NS (SE Test systems, Taiwan) torque testing machine. The sample was clamped at the XY plate upon the machine and the crown portion aligned to a custom load device with a reverse butterfly-shaped mount to perform the rotational resistance test (Fig. 2). A downward 49 N load (about 5 kg) was applied to the crown portion to simulate the axial occlusal force³³.

Five samples in each group were arranged to perform the static rotational resistance tests. Torque was applied through the butterfly-shaped crown under a rotational speed of 1.5 degree/s until the sample fractured. The remaining three samples in each group were used to perform cyclic rotational resistance tests. The condition for the torque values was ±31 N-cm³³ under a rotational speed of 3 degree/s, i.e. the sample crown portion was driven counterclockwise and clockwise to reach a positive and negative torque value of 31 N-cm in one load cycle to simulate the post and core restorations receiving the multi-vectorial nature of intra-oral force (rotational). The number of cyclic torque was continued until 1.0×10⁵ cycles or the sample presented noteworthy deformation/fracture³³. The sum of the counterclockwise and clockwise rotation degrees was recorded in each torque test for all samples. The rotation degree versus number of torque cycles was plotted to understand the failure process.

Lateral static and fatigue fracture resistance tests
Thirty six samples were also arranged into anatomical SGFR fiber post and X-Post groups to produce the lateral static/fatigue resistance tests using the Instron E3000 (Instron, Canton, MA, USA) material testing machine. The sample was mounted with a 45° inclination to the long axis of the tooth in the test machine.

Six samples in each group were arranged to perform a static lateral resistance test that was designed to drive a static compression force onto the tooth using steel cone acting on the lingual cusp as a lateral load (Fig. 3(d)). The crosshead speed was set at 0.05 mm/s until fracture occurred. The fatigue tests were carried out according to
Fig. 2 Dimensions of the artificial acrylic dentin preparation and crown/core restoration using anatomical SGFR/commercial fiber posts in an endodontically treated premolar.

Fig. 3 (a) Schematic of static and cyclic rotational resistance tests setup. (b)(c) Fracture modes of static rotational resistance tests for anatomical SGFR and commercial fiber posts, respectively. (d)(e) Fracture modes of cyclic rotational resistance tests for anatomical SGFR and commercial fiber posts, respectively. (f) Schematic of static and fatigue lateral fracture resistance tests setup. (g)(h) Fracture modes of static lateral fracture resistance tests for anatomical SGFR and commercial fiber posts, respectively. (i)(j) Fracture modes of fatigue lateral fracture resistance tests for anatomical SGFR and commercial fiber posts, respectively.
the lateral static resistance test maximum load modified with the standard ISO 14801(2007) test method to evaluate the restoration mechanical resistance in an endodontically treated tooth. The cyclic loads were set at 50, 40, 35 and 30% of the static maximum load. The test frequency was set at 6 Hz according study of Nie et al.[19]. Three specimens were tested at each cyclic load. The number of cycles at each load was recorded until $1.2 \times 10^6$ cycles, which represented 5 years of simulated function or 1 mm vertical displacement or restoration failure occurred in the sample[19].

RESULTS

The average value and standard deviation of $\delta / E_f$ for the three-point bending tested for anatomical SGFR fiber post and X-Post were listed in Table 2. The $t$-test showed that significant difference for $\delta$ ($p=0.00259$) and no significant difference for $E_f$ ($p=0.006$) were found between the anatomical SGFR fiber post and X-Post.

The maximum torque values/corresponding to the breaking angle (average value±standard deviation) in the static rotational resistance tests were listed in Table 3. The anatomical SGFR fiber post rotational resistance was found significantly higher than that of the X-Post but the corresponding breaking angles presented no significant difference. The failure modes showed that the anatomical SGFR fiber and X-Post separated from the cement layers. Both posts fractured at one third of the post but different fracture failure modes were found. Smooth fracture section for the anatomical SGFR fiber post and remaining split fiber fracture for the X-Post were found, respectively (Figs. 3(b) and (c)).

The location of a dramatic curve slope change in the rotation degree figure versus number of cyclic torque plots can be observed as the initial failure in the cyclic rotational resistance test (Fig. 4). Mapping the initial failure locations to the number of torque cycles in the anatomical SGFR fiber post were 100,000, 96,182 and 100,000 and the rotation degree sums were 7.13°, 8.23° and 5.68° for three samples, respectively. The corresponding cyclic torque/sum of rotation degrees were 61,001, 52,045 and 55,889/11.21°, 10.38° and 8.55° for the X-Post. The initial failure for the number of torque cycles in the anatomical SGFR fiber post were found significantly higher than those for the X-Post ($p=0.0006$). The failure modes also showed that the anatomical SGFR fiber and X-Post separated from the cement layers, with the smooth post fracture section only found in the anatomical SGFR fiber post and cracked flaw found only in the X-Post (Figs. 3(d) and (e)).

**Table 2** The average value and standard deviation of $\delta / E_f$ for the three-point bending tested for anatomical SGFR fiber post and X-Post

<table>
<thead>
<tr>
<th>Sample</th>
<th>X-Post</th>
<th>SGFR-Post</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flexural Strength ($\delta$) (MPa)</td>
<td>Flexural Modulus ($E_f$) (GPa)</td>
</tr>
<tr>
<td>Average</td>
<td>925.8</td>
<td>25.8</td>
</tr>
<tr>
<td>Std</td>
<td>55.90</td>
<td>0.48</td>
</tr>
</tbody>
</table>

**Table 3** The maximum torque values/corresponding to the breaking angle (average value±standard deviation) in the static rotational resistance tests

<table>
<thead>
<tr>
<th>Sample</th>
<th>X-Post</th>
<th>SGFR-Post</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Torque force (N-mm)</td>
<td>Angle (°)</td>
</tr>
<tr>
<td>Average</td>
<td>115.9</td>
<td>12.03</td>
</tr>
<tr>
<td>Std</td>
<td>11.28</td>
<td>4.488</td>
</tr>
</tbody>
</table>

![Fig. 4](image-url) The sum of the counterclockwise and clockwise rotation degrees versus number of cyclic torques in the cyclic rotational resistance tests.
Table 4 Load levels of the static maximum resistance load for anatomical SGFR fiber post and X-Post and their corresponding cycle number after restored tooth failure in fatigue tests

<table>
<thead>
<tr>
<th>% of Max. Load (%)</th>
<th>X-Post</th>
<th>Anatomic SGFR fiber post</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load (N)</td>
<td>Sample</td>
</tr>
<tr>
<td>50</td>
<td>Between 107.95 to 10.8</td>
<td>No1</td>
</tr>
<tr>
<td></td>
<td>No2</td>
<td>18,952</td>
</tr>
<tr>
<td></td>
<td>No3</td>
<td>7,124</td>
</tr>
<tr>
<td>40</td>
<td>Between 86.36 to 8.64</td>
<td>No1</td>
</tr>
<tr>
<td></td>
<td>No2</td>
<td>41,258</td>
</tr>
<tr>
<td></td>
<td>No3</td>
<td>48,214</td>
</tr>
<tr>
<td>35</td>
<td>Between 75.57 to 7.56</td>
<td>No1</td>
</tr>
<tr>
<td></td>
<td>No2</td>
<td>40,125</td>
</tr>
<tr>
<td></td>
<td>No3</td>
<td>40,824</td>
</tr>
<tr>
<td>30</td>
<td>Between 64.77 to 6.48</td>
<td>No1</td>
</tr>
<tr>
<td></td>
<td>No2</td>
<td>1,200,000</td>
</tr>
<tr>
<td></td>
<td>No3</td>
<td>1,200,000</td>
</tr>
</tbody>
</table>

The lateral static fracture resistance results were 222.7±47.18 and 215.9±25.18 (mean value and standard deviation) expressed in Newton units with no significance (p=0.393) found. Incline fracture patterns were found propagated from the buccal cervical region to the middle of the root canal in both crown/core/post restorations (Figs. 3(g) and (h)). The load levels set in the four cyclic tests for 50, 40, 35 and 30% of the static maximum resistance load for the anatomical SGFR fiber and X-Post and their corresponding number of cycles after restoration failure are listed in Table 4. A load-cycle diagram that presents the number of load cycles endured by each specimen and the corresponding peak load is shown in Fig. 5. The fatigue resistance test results concluded that the endurance limitation at 1.2×10⁶ cycles were at 30% of the maximum resistance load value, almost the same for the anatomical SGFR fiber post and X-Post (anatomical SGFR fiber post=66.81 N and X-Post=64.77 N). The fatigue test failure modes presented similar trends to those found in the static resistance tests (Figs. 3(i) and (j)).

DISCUSSION

One of the relevant problems clinicians recently faced when restoring endodontically treated teeth is the mismatch between the post space diameter and that of the post. The resin cement thickness around the fiber post can vary because flared canals develop from carious extension, trauma, pulpal pathosis and iatrogenic misadventure. Flared canals can compromise the post adaptation to canal walls. Clinical studies have revealed that when using fiber posts, the most common cause of failure is not root fracture but debonding. Excessively thick cement layers, especially at the root coronal or middle can cause post misfit, which predisposes the reconstruction to debonding. Although changing the fiber post from circular to oval profiles has been proposed in many studies to improve the post fit adaption, reducing the risk of debonding, oval post development is constrained by inherent manufacture process issues. This study proposes a novel anatomical SGFR fiber post with surface slot/notch designs that can be produced from granulate based on semi-crystalline polyamides with reinforced glass fibers, formed using mold process manufacturing. The large amount of endodontically treated dentin needed for fiber post
insertion and core/crown restorations for a series of mechanical resistance tests dictates artificial acrylic dentin with uniform prepared root canals duplicated using a CNC milling machine with 0.1 mm resolution to reduce size variations, chemical components, density and structure in natural teeth selection. Analogous approaches that also used endodontic resin blocks in vitro experiments can be found in previous studies that reveal its feasibility.  

Although the three-point bending results showed that the commercial X-Post (925.8 MPa) flexural strength was higher by about 20% over our anatomical SGFR fiber post (743.2 MPa), these values were fall into the common available flexural strength range from 600–1,149 MPa from a pool of seven commercial fiber posts examined in a study by Plotino et al. Plotino et al. also pointed out that fiber posts present the capability to resist structural fracture when its flexural strength is greater than the tooth’s corresponding strength of almost 212.9±41.9 MPa. No significant difference was found in flexural modulus between our anatomical SGFR fiber post (28.1±1.94 GPa) and X-Post (25.8±0.48 GPa). Both are higher than the 17.5±3.8 GPa tooth dentin value. Plotino et al. and other researchers addressed that fiber posts have a modulus similar to that of dentin and express better flexibility allowing a similar stress distribution to that occurring in natural teeth.  

The static rotational test result showed that anatomical SGFR fiber posts present higher resistance than the X-Post. This phenomenon might be explained by the post’s moment of inertia which can be calculated from formulas of \( m r^2/2 \) for circle and \( m (a^2+b^2)/4 \) for oval shapes, respectively (where \( m \) is mass, \( r \) is radius, \( a, b \) are main and minor axis in oval). The ratio of anatomical SGFR fiber post and X-Post is 1.67:0.91 when the mass effect is ignored. The cyclic torque test value of 31 N-cm applied in our test was according to the study of Wiskott et al. who indicated that this value was 50% of the smallest failure load in a series of implant-abutment rotational resistance tests and was suitable for application to restored teeth as the load (torque) condition. The number of cyclic torque sets as 10⁵ were not able to simulate real occlusal time and were used only for the functional test. The results indicated that the average number of cyclic torque revolutions for post fracture was 98,727 for the anatomical SGFR fiber post and 56,312 for the X-Post. The post and canal cross-section area ratio in the fracture section were also obtained as 47 and 20% for the anatomical SGFR fiber post and X-Post. These results imply that better fit adaption by the anatomical SGFR fiber post is also resistant to torque more efficiently in an endodontically treated premolar. Reasonable results were found in static/cyclic resistance test failure modes, revealing that split fracture was found in the X-Post due to its continuous (long) reinforced glass fibers. Adhesive layer debonding was found in both posts, implying that the cement bond strength was not enough to resist rotation torque.  

Although no significant differences were found in static and fatigue lateral resistance test results, the fatigue test results S-N curve can be fitted using data from 50–30% fatigue tests and linear trend curves from anatomical SGFR fiber post and X-Post showed that the anatomical SGFR fiber post presented better mechanical performance for long term lateral resistance. The number of 1.2×10⁶ cycles in the fatigue test indicated that the number of occlusal contacts that occur in vivo, Pontius et al. suggested that there are 1.2×10⁶ active cycles in 5 years of service. The load frequency 6 Hz set in the fatigue test was suggested by a study by Nie et al., who indicated that the 6 Hz test frequency was reasonable when the fiber post was exposed in an air environment to perform fatigue test. The endurance limitation at 1.2×10⁶ cycles was 66.81 N for the anatomical SGFR fiber post and 67.77 N for the X-Posts, falling into the reasonable area in previous work ranging from 50–127.4 N. All failure modes were found in the artificial dentin but not the post itself indicating that post fit adaption in root canal was not a key issue in the lateral resistance test.  

Although a novel anatomical SGFR fiber post contained short glass fibers reinforced glass with slot/notch retention designs developed using injection molding, some assumptions made in this study limit the anatomical SGFR fiber post applicability. For instance, natural teeth and viscoelastic PDL were not utilized in these experiments. The translucent characteristics of the anatomical SGFR fiber post and bonding strength between the post and resin cement are need to be warranted. The translucent characteristic between the anatomical SGFR post than in the commercial post was evaluated by X-ray. The result addressed that SGFR post in the X-ray imaging is visible in the tooth root canal but revealed low contrast when compared to commercial X-Post. Otherwise, bonding strength between the post and resin cement need to be evaluated in the further study.  

Conclusions can only be made based on the three-point bending test showing that the anatomical SGFR post flexural strength and flexural modulus were acceptable and fell into the available commercial range for continuous (long) reinforced fiber posts. The novel anatomical SGFR fiber post presented more efficient torque resistance in an endodontically treated premolar with better root canal fit adaption. However, no significant differences were found in the lateral static resistance test and endurance limitation in the fatigue test. The lateral resistance tests was not a key issue in addressing post fit adaptation to the root canal.

ACKNOWLEDGMENTS

This study supported in part by MOST project 101-2622-B-010-001-CC2, 101-2320-B-182A-001-MY2 and 103-2221-E-010-011-MY2 of the Ministry of Science and Technology, Taiwan. Authors would also like to thank to Green Point Enterprise, Taichung, Taiwan that assistant to manufacture of the anatomical SGFR fiber post.
REFERENCES


