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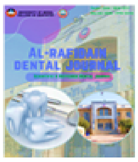

3D Finite Element Analysis of Implant-supported Fixed Partial Denture Frameworks Fabricated from Fiber-reinforced Composite and Polyetheretherketone

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Abstract

Aims: The purpose of this study was to test different design parameters for ISFPD frameworks fabricated from fiber-reinforced composite and polyetheretherketone. **Material and Methods:** 12 different framework digital designs made using the AutoCAD program were sent to Autodesk Inventor 2023 for finite element analysis (FEA), these designs included 6 different connector designs according to cross-sectional shape and height-to-width ratio as follows: (ellipse3:2, ellipse 4:3, round, ellipse3:4, ellipse2:3 and triangular9:8) with 2 different connector cross-sectional areas ($12mm^2$ and $16mm^2$) and were presented to the FEA program as two different materials (PEEK and FRC) to study stress distribution and displacement under 800N load. Stress and displacement values were used to determine the suitable framework material, connector cross-sectional area, and design. **Results:** FEA had resulted in FRC frameworks exhibiting higher resistance to bending than PEEK frameworks. $16mm^2$ connector cross-sectional area resulted in higher resistance to loading than $12mm^2$ connectors. Ellipse connectors with 3:2 height-to-width designs also resulted in the highest resistance to bending compared to other designs. Triangular designs resulted in the highest areas of stress concentration among other designs. **Conclusions:** Framework design should be considered to allow safe usage of PEEK and FRC as framework materials, FRC framework is more resistant to bending, and increasing the height of the connector increases the resistance to bending thus making ellipse designs with higher height-to-width ratio better in resistance to bending, triangular cross-section designs are not recommended.

تحليل العناصر الدقيقة لهياكل أطقم الاسنان الجزئية الثابتة المدعومة بالزرعات المصنعة من مادتى المركبات المدعمة بالألياف والبولى إيثر إيثر كيتون

الملخص

الأهداف: الغرض من هذه الدراسة هو اختبار متغيرات التصميم المختلفة لهياكل أطقم الأسنان الجزئية الثابتة المدعومة بالزرعات المصنعة من المركبات المدعمة بالألياف ومادة البولي إيثر إيثر كيتون. **المواد وطرائق العمل:** تم رسم 12 تصميمًا رقميًا مختلفًا للهياكل باستخدام برنامج AutoCAD ثم ارسلت الى برنامج Inventor لتحليل العناصر المحدودة، وقد تضمنت هذه التصميمات 6 تصميمات مختلفة للموصلات وفقًا لشكل المقطع العرضي ونسبة الارتفاع إلى العرض كما يلي: (القطع الناقص 3: 2، القطع الناقص 4: 3، الدائري، القطع الناقص 3: 4، القطع الناقص 2: 3 والمثلث 9: 8) مع منطقتين مختلفتين للموصل العرضي (12 $مم^2$ و 16 $مم^2$) وتم تعريفها إلى برنامج Inventor كمادتين مختلفتين لدراسة توزيع الإجهاد والإزاحة تحت حمل 800نيوتن .تم استخدام قيم الإجهاد والإزاحة لتحديد مادة الهيكل المناسبة ومساحة المقطع العرضي للموصل والتصميم. **النتائج:** نتج عن تحليل العناصر المحدودة أن هياكل المركبات المدعمة بالالياف أظهرت مقاومة أعلى للانحناء مقارنة بأطر بولي إيثر إيثر كيتون .اظهرت مساحة المقطع العرضي للموصل 16 $مم^2$ مقاومة أعلى للحمل من الموصلات ذات مساحة المقطع العرضي 12 $مم^2$. كما اظهرت الهياكل ذات الموصلات البيضاوية ذات نسبة الارتفاع إلى العرض 3: 2 مقاومة أعلى للانحناء مقارنة بالتصميمات الأخرى. اظهرت التصاميم المثلثة أعلى مناطق تركيز الإجهاد مقارنة بالتصاميم الأخرى. **الاستنتاجات:** ينبغي الاخذ بنظر الاعتبار تصميم الهيكل للسماح بالاستخدام الآمن للمركبات المدعمة بالالياف والبولي ايثر ايثر كيتون كمواد هيكلية، هيكل المركبات المدعمة بالالياف أكثر مقاومة للانحناء، زيادة ارتفاع الموصل يزيد من مقاومة الانحناء وبالتالي جعل التصميمات البيضاوية ذات نسبة الارتفاع إلى العرض الأعلى أفضل في مقاومة الانحناء، لا ينصح بتصميم الجزء الموصل في الهياكل بشكل مثلث.

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INTRODUCTION

ISFPD in different forms can be used predictably to rehabilitate patients with edentulous or partially dentate jaws, the current study focused on treating patients where using remaining teeth to obtain a fixed prosthesis is not possible (1).

Many materials are commonly used for framework construction such as polyetheretherketone (PEEK) which belongs to the polymer group family and is identified as a “polyaromatic semi-crystalline thermoplastic polymer”. PEEK has been used both in tooth-supported crowns and in ISFPD due to its lower cost and relative esthetic properties compared to the metallic framework (2).

Fiber-reinforced composites (FRCs) are a group of non-metallic biomaterials that were first used in dental applications in the early 1960s. It has been used in removable and fixed prosthodontics (3 & 4).

FEA is a computational technique originally developed by engineers to model the mechanical behavior of structures such as buildings, aircraft, and engine parts, it simulates either 2D or 3D designs (5).

FEA has attracted the interest of dental and medical researchers and is nowadays one of the furthermost successful engineering numerical techniques. It has been also utilized to predict the mechanical behavior and stress distributions of dental crowns, restorations, and FPDs (6).

3D FEA is beneficial for frameworks with potentially sophisticated shapes such as dental crown restorations and dental implants, however, there are other limitations for FEA such as assuming ideal test circumstances, giving mesh-dependent results, and being a second line of testing when other tests are not available (7).

In this study, the null hypothesis was proposed that no difference was present in the stress distribution and load/displacement behavior for two different framework materials with different connector designs and different connector cross-sectional areas of the ISFPD framework. So, the current study aims to study the stress distribution using the FEA of the tested framework materials and designs and study the bending load/displacement behavior using the FEA of the tested framework materials and designs.

MATERIALS AND METHODS

In this study, 3D designs of the bone block, two implant abutments (lower first premolar and first molar), and a framework of an FPD (from lower first premolar to lower the first molar) were drawn using AutoCAD computer software according to the real measurements obtained from the manufacturer standards (1mm thickness of retainers with shoulder type finishing line), implant fixture and its interface with bone is out of study concerns, it was not drawn to simplify analysis.

The connector part of the framework for the drawn design was further edited to obtain 12 different proposed framework designs for two different framework materials (12 for

PEEK and 12 for FRC), as shown in Figure (1).

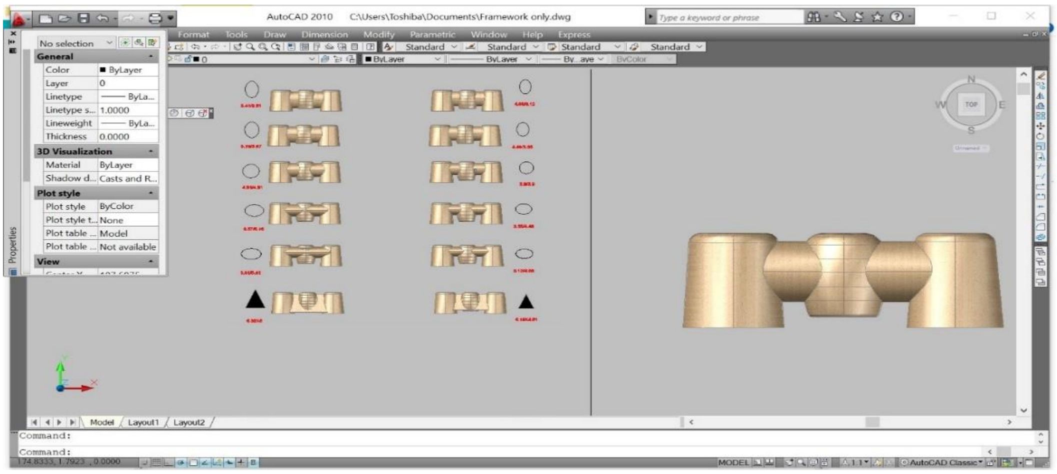

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Figure (1): 12 different connector designs for a framework of a FPD drawn using AutoCAD program

The 12 designs were exported as (*.sat) extension files to be accepted by the FEA program (Autodesk Inventor 2023) to be eventually analysed for stress distribution and deflection, as shown in Figure (2).

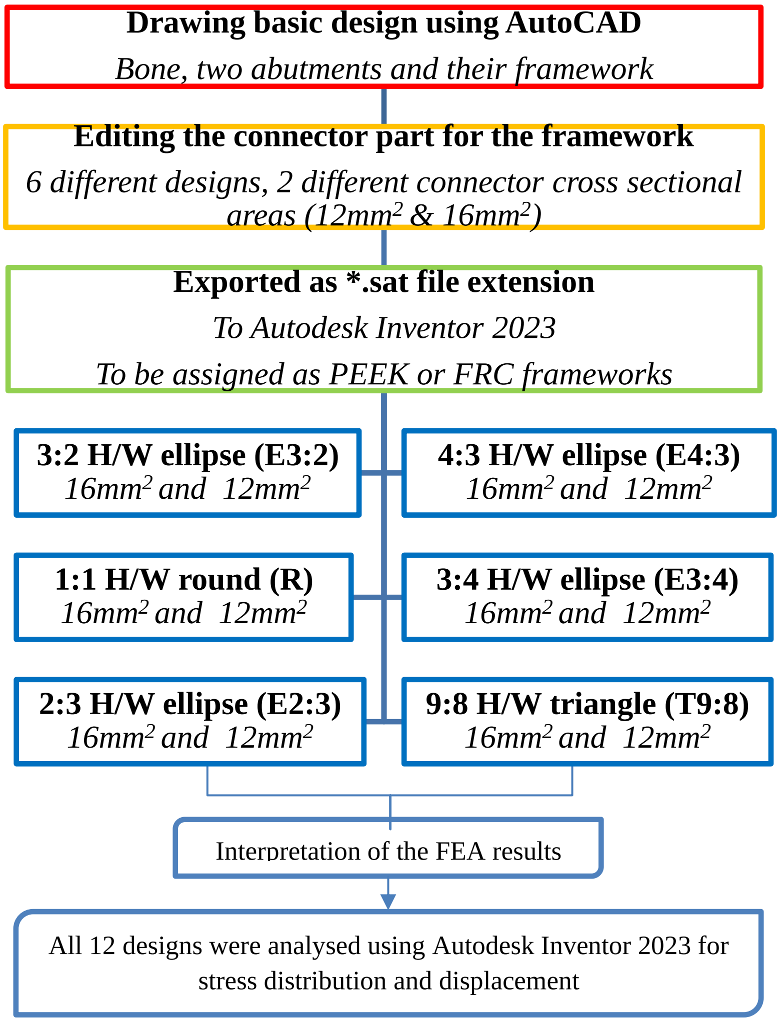

Figure: (2): Experimental design of the FEA for 2 framework materials and 12 different framework designs

Samples were named using acronyms that represent their material, connector cross-sectional area, and connector design, for example, P16E3:2 means **P**EEK framework, **16**mm^2 connector cross-sectional area, **E**llipse connector cross-section, **3:2**height to width ratio.

After exportation to Autodesk Inventor 2023, all involved materials were considered to be isotropic, homogenous, and linearly elastic, and their properties (Elastic modulus and Poisson's ratio) were introduced to the program (8,9), as shown in Table (1).

Table (1): Elastic modulus and Poisson's ratio of used materials

Materials	Modulus of Elasticity (GPa)	Poisson's ratio
Cortical bone	13.7	0.3
FRC	26	0.398
PEEK	3.6	0.36
Titanium	110	0.35

The interface between the bone, abutment, and framework was simulated to be rigidly bonded. The model constraints were the inferior surface of the base model (9).

An (800N) loading force was applied to the center of the occlusal surface of the pontic in (Y-axis) and perpendicular to the bone surface for all model designs, the auto-meshing routine was performed. The total number of elements per model ranged from (43864 to 54214) and the number of nodes was ranged (from 27717 to 33879) depending on the cross-sectional area, shape, and height-to-width ratio of the framework connector design, as shown in Figure (3) (10 & 11).

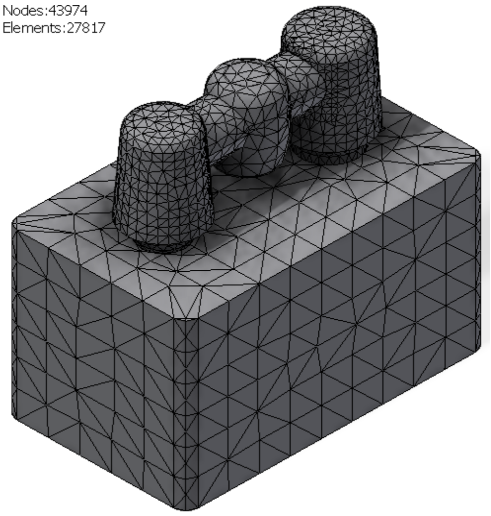

Figure (3): Mesh view of the model using Autodesk invertor 2023 program

The simulation was performed and the results were displayed and analyzed. Both numerical and graphical were adopted (12).

Assessments of stress distribution on the framework model elements for each design were done using maximum and minimum stress values, which are obtained by pressing the "maximum" and "minimum" buttons in the program interface after selecting the "stress" tab which indicates the tensile and compressive stresses respectively. The displacements at the lowest point of the pontic were evaluated as a reference of the framework deflection to investigate the effect of different design parameters, the "probe" tool in the program was used to obtain the maximum displacement at the lower border, as shown in Figure (4) (13,14).

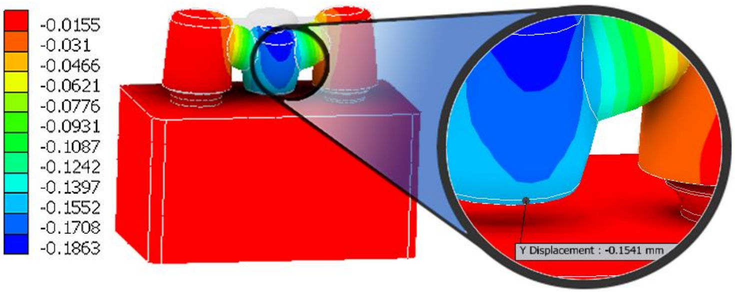

Figure (4): FEA model showing the selected reference point for measuring displacement value

RESULTS

For the stress distribution, the simulation displayed the normal compressive and tensile stresses. The normal stress values for all the framework assemblies are shown in Table (2). The programmatic stress analysis results were presented in a scale that is color-coded indicating the stress values (the red color indicates a high value while the blue indicates a low value), as shown in Figure (5).

Table (2): Normal compressive and tensile stresses (in MPa) for the framework obtained using FEA for all designs on 800N load

PEEK			FRC		
Designs	**Normal compressive stress (MPa)**	**Normal tensile stress (MPa)**	**Designs**	**Normal compressive stress (MPa)**	**Normal tensile stress (MPa)**
P16E3:2	-97	64.3	**F16E3:2**	-105	94.1
P12E3:2	-89.5	39.8	**F12E3:2**	-105	54.3
P16E43	-118.4	49.6	**F16E4:3**	-132.7	74.5
P12E43	-119.1	74.3	**F12E4:3**	-149.1	109
P16R	-106.5	44.2	**F16R**	-148.3	74.3
P12R	-124.5	89.5	**F12R**	-139.1	109.4
P16E3:4	-123.6	69.8	**F16E3:4**	-152.6	104.9
P12E3:4	-154.8	93.7	**F12E3:4**	-174.3	140
P16E2:3	-118.6	79.5	**F16E2:3**	-141.9	124.4
P12E2:3	-106.7	77	**F12E2:3**	-124.9	98.7
P16T9:8	-628	68.7	**F16T9:8**	-816.3	67.4
P12T9:8	-711.4	110.6	**F12T9:8**	-892.8	132.3

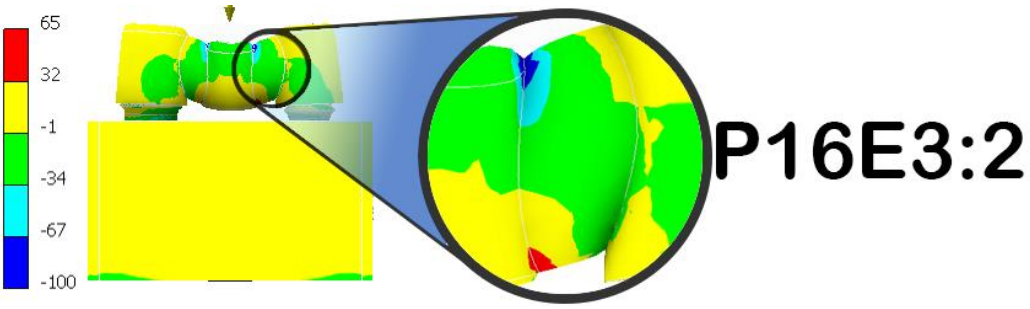

Figure (5): Normal compressive and tensile stresses (in MPa) for P16E3:2 design

The numerical results for displacement under load were obtained from the lower border of the pontic, these values reflected resistance to load for different designs of different tested parameters. The values were tabulated in Table (3).

FEA results showed that PEEK frameworks had higher displacement than those of FRC for each specific connector design and cross-sectional area, as shown in Figures (5 &6).

Table (3): Displacement (in μm) obtained using FEA for all designs at the lower border of the pontic on 800N bending load

PEEK		FRC	
Designs	**Displacement(μm)**	**Designs**	**Displacement(μm)**
P16E3:2	114	**F16E3:2**	26
P12E3:2	143	**F12E3:2**	30
P16E4:3	139	**F16E4:3**	33
P12E4:3	146	**F12E4:3**	43
P16R	148	**F16R**	36
P12R	154	**F12R**	44
P16E3:4	159	**F16E3:4**	40
P12E3:4	201	**F12E3:4**	46
P16E2:3	167	**F16E2:3**	41
P12E2:3	214	**F12E2:3**	48
P16T9:8	139	**F16T9:8**	38
P12T9:8	166	**F12T9:8**	42

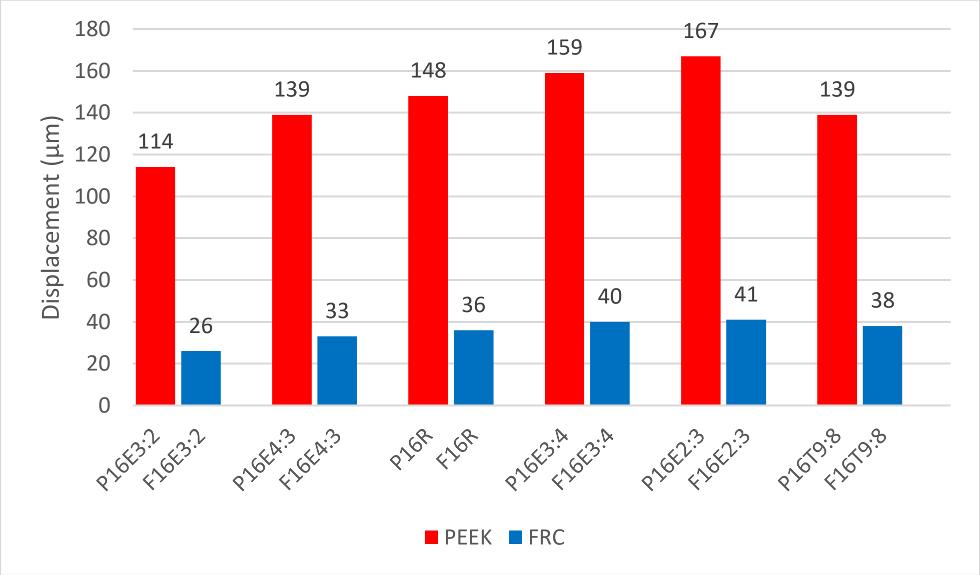

Figure (6): FEA reports for the effect of two different framework materials on displacement(μm) for frameworks with 16mm^2 cross-sectional area

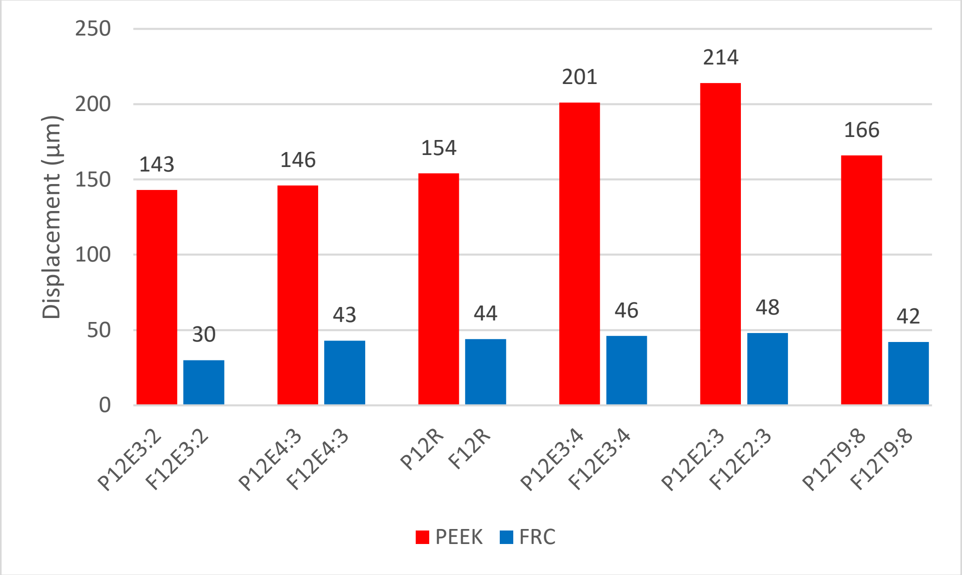

Figure (7): FEA reports the effect of two different framework materials on displacement(µm) for frameworks with a 12mm^2 sectional area

DISCUSSION

Although PEEK and FRC materials are widely evaluated in orthopedic, periodontology, and dental implantology, published peer-reviewed studies evaluating these materials as a cost-effective and biocompatible material for three-unit FDPs or other lab work are still scarce (15 & 16).

Therefore, the current study has conducted FEA to evaluate the effect of these materials on framework resistance to displacement under load with different connector designs and cross-sectional areas, to allow screening of PEEK and FRC as potentially suitable materials in the latter application.

Stress distribution results

FEA allows the calculation and observation of the stress distribution in each part of a geometrically complex structure such as FDP frameworks (17). To study the stress distribution for different test parameters, the values of normal stresses were shown in Table (2) and Figure (5).

FEA for this study has shown that during axial compressive loading of the pontic, the highest stress values were at the connector part of the framework assembly, this is due to the connector having the least value of area moment of inertia (I) (which is a dimension-dependent property of the design that reflect its resistance to bending) (18).

The gingival side of the area of the connector was subjected to the highest tensile stress while the occlusal surface of both connectors and the loading point on the pontic were subjected to the highest compressive stress for all designs, as shown in Figure (5). This finding was in approval with other FEA and photoelastic studies that found that these areas were considered as stress concentration and fracture initiation areas (14 & 19).

For the effect of connector cross-sectional area on stress distribution, this study found that connectors of 12 mm^2 cross-sectional areas had higher stress levels than 16 mm^2 connectors for the same framework material and design, this was because reducing the area for the same geometry means reducing the value of (I). This result was in agreement with other studies that found the same correlation between connector cross-sectional area and stress distribution (14 & 20).

For different connector designs, designs with higher height-to-width ratios had the least stress values, this is also due to a higher value of (I). This study also found that triangular connector designs had the highest compressive stresses in the occlusal side of the connector among other designs. These stresses overwhelm the material's compressive strength and contraindicate the safe use of this design for the tested materials for posterior teeth replacement, this is due to the triangle apex that had a small area. However, due to its wide base, the triangle design had an acceptable tensile stress value. This result is approved with another study that relates the sharp edges in the connector with the increase in stress levels and lower stress levels in rounded edges due to wider area (14).

However, this result is in contrast with another practical study that found better fracture resistance for the triangular connector design, this difference could be due to the CAM's inability to reproduce such sharp edges (10).

Therefore, the first part of the null hypothesis which stated that there was no effect of the investigated framework materials, connector cross-sectional area, and connector design on the stress distribution loading was rejected.

FEA displacement results

The displacement values were obtained from the lower point of the pontic for all samples to standardize the readings among samples and to avoid the local faulty displacement (indentation) (14).

The study found that the load-displacement of PEEK frameworks was higher than that of FRC frameworks for all cross-sectional areas and designs as shown in Table (3) and Figures (6 & 7).

This can be explained by the fact that the elastic modulus of FRC with its cross-linked polymer matrix is higher (26 GPa) than the elastic modulus of PEEK (3.6 GPa) and that the lower elastic modulus of the framework material generated a larger bending of the prosthesis under functional loads. Because of this feature, FRC frameworks allow clinically smaller connectors and thinner crowns to be used compared with PEEK with less chance of distortion or veneer breakage (15,21, 22 & 23).

This finding was consistent with other studies that found an increase in framework flexibility when using materials with a lower elastic modulus (24 & 25).

Therefore, the first part of the null hypothesis which stated that there is no effect of the investigated framework materials on the amount of displacement under loading was rejected.

According to FEA used in this study to evaluate the effect of two framework connector cross-sectional areas on displacement under loading, it was found that the load-displacement of 12mm^2 frameworks was higher than that of 16mm^2 frameworks for all designs and both framework materials as shown in Table (3) and Figures (6,7) which is related to the fact that increasing the connector cross-sectional area for a specific cross-section geometry increases the value of (I) and eventually produces less displacement under load (10,26).

This finding was in approval with other studies which concluded that increasing the connector cross-sectional area has a favorable effect on the framework resistance to fracture and displacement (14,23,26).

Therefore, the null hypothesis which stated that there is no effect of the framework connector cross-sectional area on the amount of displacement under loading was rejected.

FEA also found that frameworks with elliptical 3:2 height-to-width connectors had the least amount of displacement under load for both framework materials and connector cross-sectional areas as shown in Table (3) and Figures (6 & 7). This is illustrated in the theory of deflection of a beam, where the height cubed is inversely proportional to the deflection. Therefore, increasing the height will increase (I) exponentially (27). This study agrees with other studies that found an effect of connector design on the bending resistance of the framework and that the higher the loads the framework will be exposed to, the greater the height of the connector required (19 & 27).

These results however disagreed with the results found in another study that resulted in no effect for the cross-sectional shape of the connector that was designed to assume a circular or oval shape with a height/width ratio of 1:1, 3:4, or 2:3, this could be due to the different methods and different test parameters (26).

Therefore, the null hypothesis which stated that there is no effect of the framework connector design on the amount of displacement under loading was rejected.

CONCLUSIONS

1. Framework design and dimensions should be considered to allow the safe usage of PEEK and FRC as framework materials in FPDs (FPD).
2. FRC frameworks are more resistant to displacement than PEEK frameworks.

3. Increasing the framework connector cross-sectional area increases resistance to the bending of the framework.
4. Increasing the height of the framework connector about the width increases the resistance to bending, even if the cross-sectional area is the same.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication and/or funding of this manuscript.

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