The effect of composite bonding spot size and location on the performance of poly-ether-ether-ketone (PEEK) retainer wires

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ABSTRACT

Background: Poly-ether-ether-ketone(PEEK) has been introduced to many dental fields. Recently it was tested as a retainer wire following orthodontic treatment. This study aimed to investigate the effect of changing the bonding spot size and location on the performance of PEEK retainer wires.

Methods: A biomechanical study involving four three-dimensional finite element models was performed. The basic model was with a 0.8 mm cylindrical cross-section PEEK wire, bonded at the center of the lingual surface of the mandibular incisors with 4 mm in diameter composite spots. Two other models were designed with 3 mm and 5 mm composite sizes. The last model was created with the composite bonding spot of the canine away from the center of the crown, closer to the lateral incisor. The linear displacement of the teeth, strains of the periodontal ligament, and stresses in PEEK wire and composite were evaluated. The data was numerically produced with color coded display by the software. Selected values were tabulated and compared among models.

Results: The amount of linear displacement and strain was very low. Stresses in the wire and composite were affected by the size and position of the composite bonding spot. The safe limits were identified at 235 MPa for PEEK and 100 MPa for composite. The basic model had a von Mises stress in the PEEK wire of 122.09 MPa, and a maximum principal stress in the composite of 99.779 MPa. Both stresses were within the safe limits, which means a lower risk of failure in PEEK and composite. All other models had stresses that exceeded the safe limit of the composite. The 3 mm composite model was the only one that developed stresses in the wire more than the safe limits of PEEK.

Conclusions: Within the limitations of this study, bonding PEEK wires with 4 mm bonding spots to the clinical crown center provided the best mechanical performance of the wires and spots; otherwise, the mechanical properties of the wire and composite would be affected and, therefore, might affect the retention process.

Keywords: Retention, PEEK, Finite element analysis **(Received: 28/2/2021, Accepted: 29/3/2021)**

INTRODUCTION

The teeth have a tendency to return to their initial position following orthodontic treatment; all efforts are attempted to keep them in their corrected position [1]. When the teeth move, the alveolar bone and the periodontal ligament undergo changes. It would take a considerable time for a complete re-organization to finish [2]. Life-long or indefinite retention is a routine practice among orthodontists [1, 3]. When instability is anticipated, fixed retention is considered [4, 5]. Most patients require a fixed retainer to keep their lower anterior teeth stable after treatment [6]. Knierim [7] was the first to introduce fixed retention using a solid 0.028" stainless-steel wire in 1973. Since then, many materials were utilized as fixed lingual retainers, including but not limited to: multi-stranded stainless-steel wires, elgiloy blue, glass fiber-reinforced, copper-nickel-titanium, polyethylene ribbon-reinforced, and active nickel-titanium wires [8-10]. Each retainer has its downsides, like wire failure, unraveling, bond breakage, allergy, etc. [10, 11].

Retainers should have qualities like being esthetic, biocompatible, adaptable with ease to the lingual surface [1], capable of resisting deformation, passive at the time of placement [12], having adequate flexibility to allow physiologic movement of the teeth, which helps to reduce stress concentration within the composite. Lastly, it should have good bonding to resin adhesives [8].

The PEEK is being considered as a substitute for metal alloys in dental practice [13]. It is known for its outstanding mechanical properties. When processed by computer-aided design/computer-aided manufacturing (CAD/CAM), it shows lower deformations and higher fracture loads than can be achieved by other processing techniques. Its field of use is expanding in light of its excellent milling and grinding properties, which highlights its potential in dentistry [14]. In orthodontics, PEEK was suggested as an alternative archwire to nickel-titanium wires with self-ligating brackets, and it was also tested as a fixed space maintainer [13, 15]. In a laboratory study, PEEK was compared to a group of metallic retainer wires; it performed as good as the conventional metal wires; hence it was suggested to be tried clinically [16].

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Finite element analysis (FEA) is a computational method that can assess in a non-destructive and repeatable way the complex biomechanical behavior of heterogeneous materials and structures with complex geometries [17]. In the field of orthodontics, it had been used in many aspects like tooth movement, treatment techniques, temporary anchorage devices, and assessing orthodontic materials [18-22].

This study aimed to investigate the effects of using different composite bonding spot sizes and changing the distance between the bonding spots of the lateral incisor and the canine by assessing three-dimensional (3D) finite element models.

MATERIALS AND METHODS

Materials

The material under investigation is the white blocks DD-peek-MED (DentalDirekt, Spenge, Germany), composed of PEEK ≥ 80%, and titanium dioxide <20%, according to the manufacturer's website [23].

Methods

The three-dimensional design of the model

Using the Fusion 360 software (Autodesk, California, USA), the lower anterior teeth were modeled as per the individual description stated in Wheeler's dental anatomy textbook [24]. The teeth model was imported to SolidWorks 2018 software (Dassault Systèmes, Vélizy, France). The y-axis represented the vertical plane, the x-axis represented the transverse plane, and the z-axis represented the sagittal plane. The roots were covered with PDL represented by a 0.2 mm uniform layer, then spongy bone, and finally, cortical bone.

The retainer wire was modeled in a cylindrical form with a 0.8 mm diameter extending along the lingual surface of the lower anterior teeth without contact. The wire was modeled in two halves so that the upper one would be exposed to the forces from the oral direction; these halves were later merged. The resin bonding spots were modeled, covering the PEEK wire on the center of the clinical crowns (Figure 1).

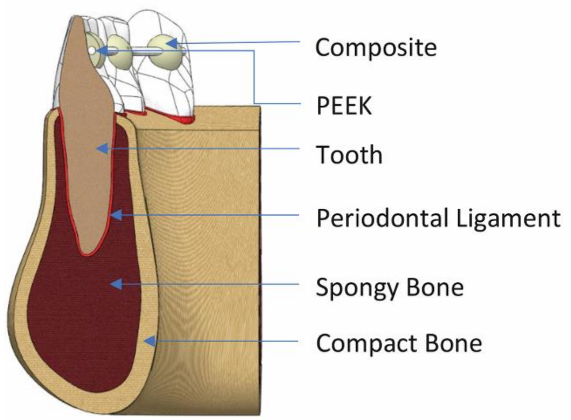

Figure 1 A cross-section showing the different structures of the model.

Modified models

A. Composite diameter: two models were created using two bonding spot sizes, 3 and 5 mm.
B. Composite location: the location of the bonding spot on the canine was modified so that it was not at the center of the clinical crown; to reduce the distance between the bonding spots.

Obtaining elastic modulus and yield strength of PEEK

The flexural properties of PEEK were obtained by following the American Society for Testing and Materials (ASTM) standards F2026-17 and D790-03. A three-point bending test was performed on eight test specimens, using a universal compression and tension machine (Tinius-Olsen, Pa., USA) with a 1 kilo-newton load cell. The test specimen dimensions were 1.6 mm in thickness, 30 mm in length, and 12.7 mm in width. The support span was 25 mm, and the cross-head diameter 5 mm. The calculated cross-head speed was 0.65 mm/min.

Finite element analysis

Material properties

The models were imported into ANSYS Workbench 18.2 (ANSYS, Canonsburg, Pa). The static structure simulation was selected for the 3D model. All materials were assumed linearly elastic, homogenous, and isometric for simplification purposes. Table 1 shows the properties of the materials that were determined from previous work [25-27] and the three-point bending test on PEEK.

Table 1 Material properties

Structure	Young's Modulus (MPa)	Poisson's Ratio
Tooth	20300	0.26
PDL	0.667	0.49
Spongy Bone	13400	0.38
Cortical Bone	34000	0.26
Composite	16600	0.24
PEEK	5130	0.39

Boundary condition and loading

The bone segment was fixed at the posterior surface of both ends in all directions. The contacts between teeth and PDL, PDL and spongy bone, spongy bone to compact bone, and composite to teeth and PDL were set to "bonded." According to the work of Serra and Manns [28], a 295.3 N (that equals the maximum biting force on the anterior teeth) was applied to the upper half of the wire at a 45° angle to the horizontal plane (Figure 2) [25]. This angle corresponds to the direction of force being applied in a vertical direction while the mouth is widely opened for biting. Two force components were used to achieve this, a vertical component of -201.75 N and a horizontal component of 201.75 N.

Convergence Tests

The convergence tests were performed to identify the smallest mesh size that will yield acceptable results without jeopardizing the results. The mesh size was gradually reduced from 0.4 mm to 0.1 mm, while all other variables were unchanged. The results were evaluated at three vertices on the PEEK, PDL, and tooth. Multiple parameters were considered, including total deformation, equivalent von Mises stress in the PDL, and finally, the equivalent von Mises stresses for PEEK. A 5% variation was considered acceptable, as it was assumed to have no clinical significance. Due to the nature of the finite element analysis, which produces a single value for each parameter per model, statistical analysis was not possible. The data was numerically produced with color coded display by the software. Selected values were tabulated and compared among models.

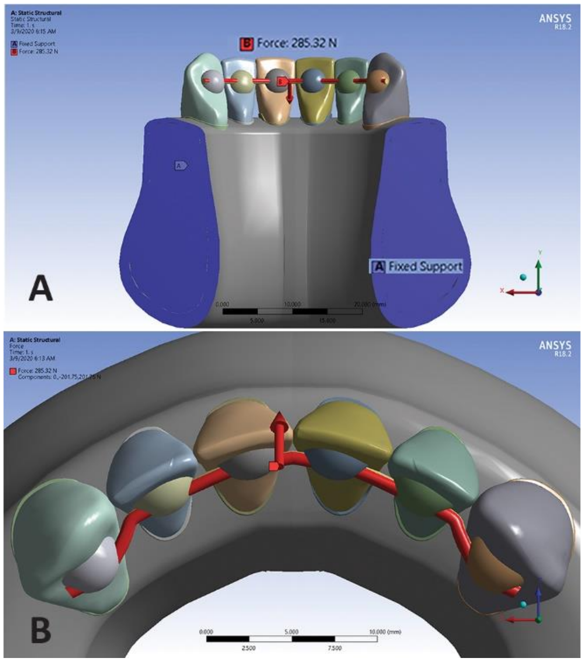

Figure 2 Boundary conditions and loading, A, Lingual view showing the fixed lingual surfaces of bone (colored blue), B, a close-up occlusal view.

RESULTS

The yield strength and modulus of elasticity

The three-point bending test results of PEEK were averaged to a yield strength of 235 MPa, and modulus of elasticity of 5130 MPa. This data was used to feed the FEA.

The convergence tests

The 0.2 mm mesh size provided acceptable accuracy, with changes less than 5%. A finer mesh would have no added value, but it would significantly increase computation time and model size (table 2). Therefore, the 0.2 mm mesh size was used for all models. The examined parameters were as follows (Figure.3): total deformation of the whole model (TDM), total deformation of PEEK wire (TDP), elastic strain of the whole model (ES), maximum principal stress in the composite bonding spots (MxPS-C), maximum principal stress in the PEEK wire (MxPS-P), minimum principal stress in the PEEK wire (MnPS-P), maximum von Mises stress in the PEEK wire (MxVM-P), and safety factor (SF). For all models, both the TDM and TDP were minimal; they were around 0.2 mm. The findings of the four models are shown in Table 3 and Figure 4.

Table 2 The Results of Convergence Test

Mesh size (mm)	Total deformation of tooth vertex (mm)	Change (%)	Von Mises stress PDL vertex (MPa)	Change (%)	Von Mises stress of PEEK vertex (MPa)	Change (%)	Nodes	Element
0.4	0.188	N/A	0.997	N/A	24.285	N/A	413,601	227,927
0.3	0.189	0.5	0.076	-92.4	8.465	-65.1	693,815	386,680
0.2	0.190	0.5	0.082	7.9	12.646	49.4	1,760,868	1,000,075
0.1	0.187	-1.6	0.084	2.4	12.782	1.1	8,014,078	4,617,393

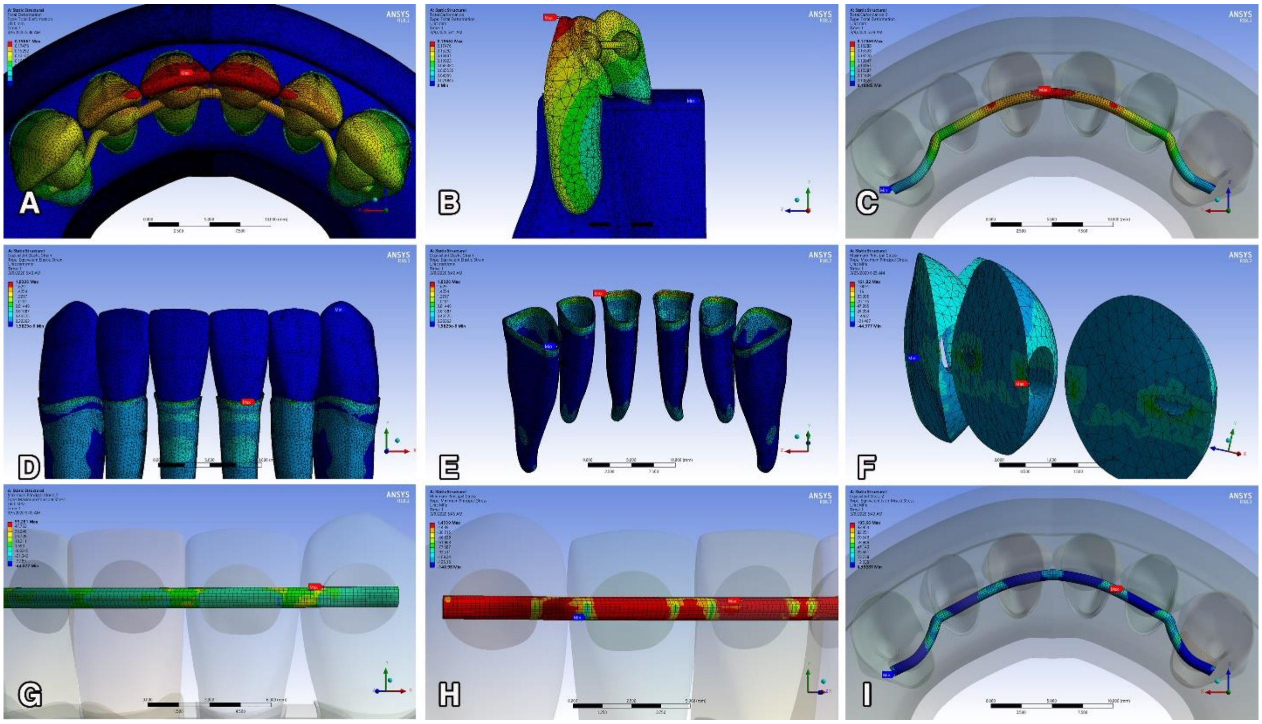

Figure 3 The parameters investigated in this study. (A) Total deformation of the whole model(occlusal view), (B) Total deformation of the whole model (cross-sectional view), (C) Total deformation of the PEEK wire, (D) Maximum elastic strain of the PDL (Frontal view), (E) Maximum elastic strain of the PDL (Lingual view showing PDL only), (F) Maximum principal stress in composite, (G) Maximum principal stress in PEEK wire, (H) Minimum principal stress in the PEEK wire, (I) Equivalent von Mises stress in the PEEK wire.

Table 3 Stresses, strain, and deformations associated with different models

	Parameters	3mm	4mm	5mm	Modified position
1.	Total deformation of the whole model(mm)	0.198	0.194	0.19	0.202
2.	Total deformation of the PEEK wire (mm)	0.175	0.167	0.162	0.175
3.	Elastic strain	1.849	1.817	1.78	1.893
4.	Maximum principal stress in the composite bonding spots (MPa)	267.82	99.779	134.03	153.12
5.	Maximum principal stress in the PEEK wire (MPa)	220.7	79.219	48.161	39.762
6.	Minimum principal stress in the PEEK wire (MPa)	-288.0	-204.70	-89.786	-144.4
7.	Maximum von Mises stress in the PEEK wire (MPa)	241.3	122.09	54.73	94.201
8.	Safety factor	0.974	1.925	4.294	2.495

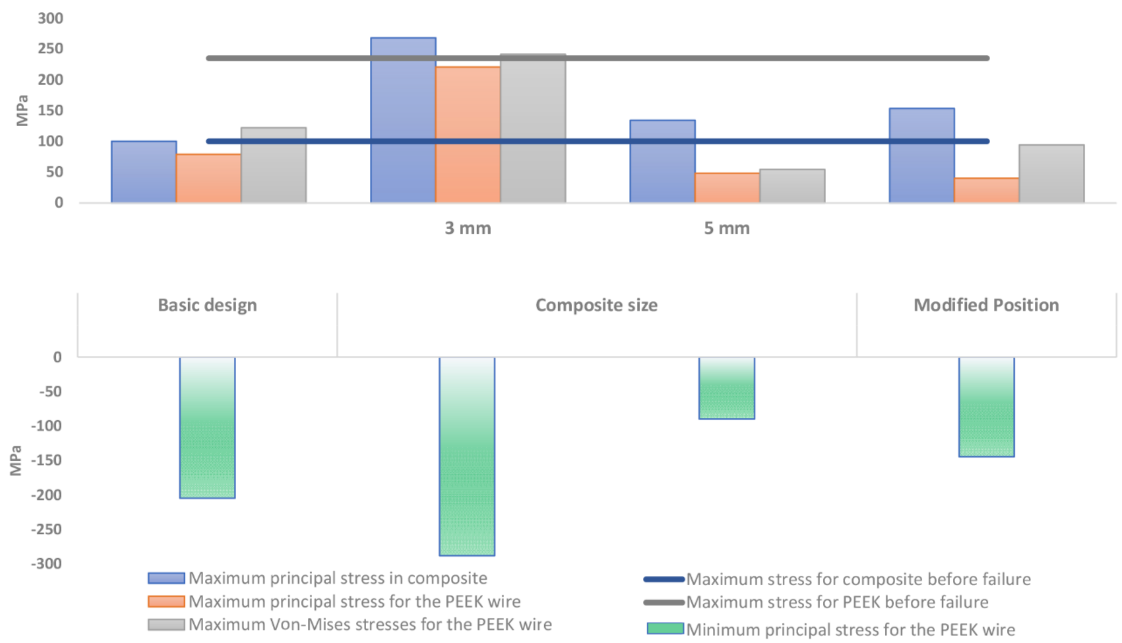

Figure 4 The effect of the size and position of composite bonding spots on maximum principal stress in composite and PEEK, and maximum von Mises stress in PEEK (Up), and minimum principal stress in PEEK (Down). The blue and grey lines represent the safety limits for composite spots and PEEK wires respectively.

The greatest TDM was at the tip of the central incisor, while the greatest TDP was at the upper margin of the wire. The difference in ES was also minimal. It occurred at the upper distolabial margin of the lower central incisor PDL.

As shown in Figure 5, the basic model and the 5 mm composite models shared a common stress concentration area at the distal margin of the composite of the lateral incisor. The failure region for the 3 mm composite model was at the mesial margin of the bonding spot of the lateral incisor. Finally, the model with the modified composite position had a failure point more anteriorly, at the lateral side of the lower central incisor. All models had their failure regions associated with compressive stress.

All models, except the 3 mm composite model, had a safety factor greater than one. The 3 mm composite model showed significant deterioration in the performance of the PEEK wire. It had greater stresses than all other models. The most remarkable change was in the MxPS-P. On the other hand, the 5 mm composite model showed lower stress values for the PEEK than the basic model. The MnPS-P and MxVM-P were well below half that of the basic model. Nonetheless, the MxPS-C was increased by greater than 30%. The SF was the greatest among all models; it was more than double that of the basic model at 4.294.

The modified composite position model showed an improved performance of the PEEK wire, with reduced stresses compared to the basic model. The greatest reduction was in the MxPS-P, which was almost half that of the basic model. While the SF for the PEEK was increased by around 30%.the MxPS-C was increased by more than 50%.

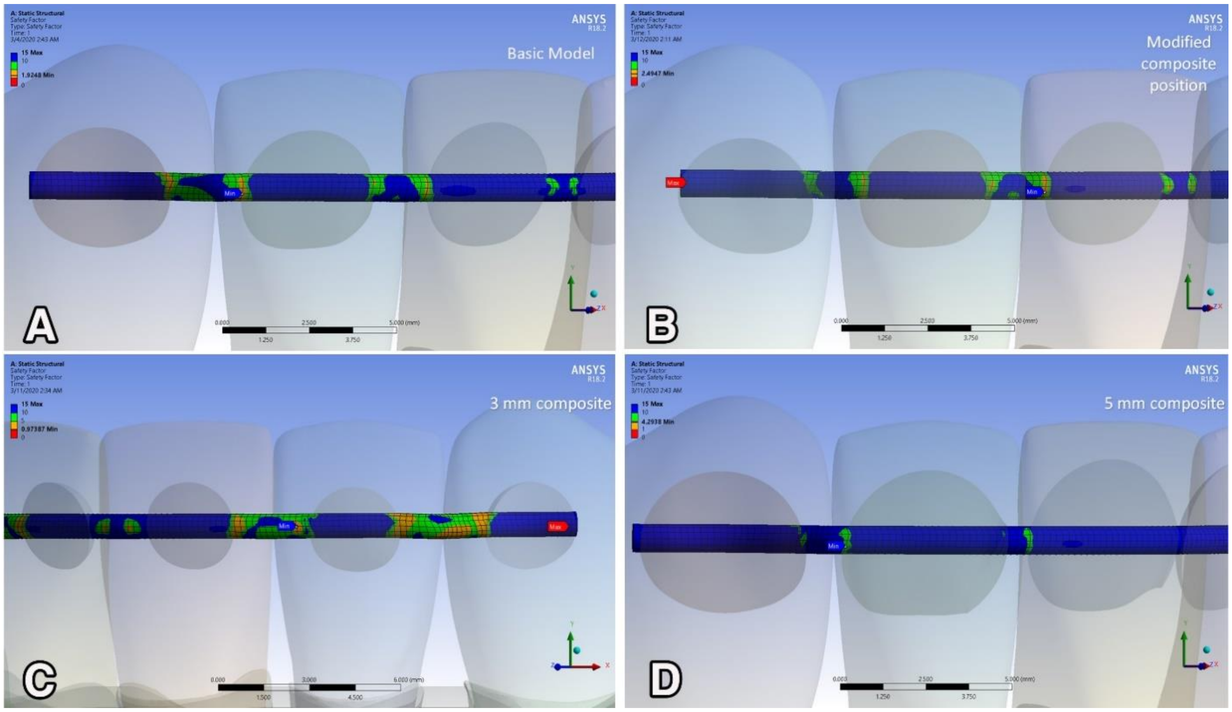

Figure 5: The safety factor of PEEK in four models, the blue indicator shows the lowest safety factor value i.e, failure site. (A) basic model, (B) modified composite position, (C) 3 mm composite bonding spot, (D) 5 mm composite bonding spot.

DISCUSSION

Multi-stranded wires had been the most common type of fixed retainers for decades [11]. The PEEK is a member of the family poly-aryl-ether-ketone, which is known for good strength, high mechanical fatigue strength, and having a very good chemical resistance [29]. It has several advantagesover stainless-steel wires; these include providing better fitness as it is fabricated by CAD\CAM, chemical resistance to all oral fluids, can be used in patients with nickel hypersensitivity, improved esthetics, and finally, lacking latent activation forces, which means reduced post retention tooth movement.

Recently, PEEK was tested as a retainer wire using wire segments bonded to the lingual surface of bovine incisors [16]; the results were promising for using PEEK as a retainer wire. This laboratory study had two basic aspects: first, using molds to standardize the quantity of the applied composite resin adhesives; second, a two-millimeter distance. Furthermore, the two-millimeter distance may represent the distance between the bonding spots of the central and lateral incisors, but the distance between the lower canine and lateral is different. Therefore, it was assumed that some clinicians might apply a smaller or larger amount of composite (supposedly 3 and 5mm in diameter, respectively). Bonding to the center of the clinical crown is the position used by clinicians and is the one used in the basic model. A more mesial modified position was created to approximate the two millimeters distance between the bonding spots, which was used in the laboratory study.

Modeling the wire in two halves was performed to better simulate the oral conditions, where the superior-posterior surface is the one exposed to forces resulting from oral functions. This methodology was not adopted before in the limited number of similar articles [27, 30, 31]. The force was applied to the wire surface only to simulate the direct transmission of biting forces to the fixed retainer wire, representing a commonly seen mode of failure of mandibular retainers [32].

Stresses can be described as principal stresses, shear stresses, and von Mises stresses. The first type denotes those taking place along the principal axes: z, y, and x. These can have a positive value indicating tensile stress or a negative value indicating compressive stress. The second type describes stresses occurring around each two planes z/x, x/y, and z/y. The last type represents a theoretical value resulting from a formula that combines the principal and shear stresses into single non-directional equivalent stress. Therefore, its value is always positive and is often referred to as equivalent stress[33].

A material fails when the von Mises stress equals or exceeds the yield strength. This is best used for ductile materials. On the contrary, principal stresses are used for the prediction of brittle materials failure [17, 33]. The safety factor is used to describe the relationship between the von Mises stress and the yield strength. Therefore, if the SF was smaller than one, this indicates a possible mechanical failure for the material at this point; conversely, if it was larger than one, this indicates a safe condition with that level of stress [34].

The effects of altering the size and position of the bonding spots on the amount of displacement (total deformation of the model and the PEEK wire) and the PDL straining were of minimal value, which seemed to be limited to the PDL thickness, as the rigid bone structure prevented further displacement.

No model had a failure at the central region between the central incisors. This may be attributed to that both central incisors move to the same degree, which keeps stresses at the mesial side of the bonding spots lower than stresses at other regions.

The failure region (i.e., with the lowest SF) for the basic and the 5 mm composite bonding spot models was distal to the lateral incisors. This could be related to that this region is the longest span within the mandibular anterior teeth. Additionally, the other spans are very short with the latter model, making the wire more rigid.

The more mesial position of the bonding spot relative to the center of the canine reduced the span between the lateral and the canine, making the wire more rigid. The failure point shifted more anteriorly to be distal to the central incisors.

In the last model, reducing the spot size to 3 mm increased the span length, which increased the flexibility of the wire. The failure point was mesial to the lateral incisor.

Except for the 3 mm model, the PEEK retainer wires would withstand the maximum biting force, but the composite may not. The orthodontic adhesive used by Kadhum and Alhuwaizi [16] was Transbond XT light cure orthodontic adhesive (3M Unitek, Monrovia, CA, USA). This bonding material has 77 wt% silica filler particles; its flexural strength was reported by Ryou et al. [35] as 113 (14.3) MPa, while Gama et al. [36] reported it to be 152.7 (31.4) MPa. These findings propose that we should be looking for maximum principal stress close to 100 MPa to avoid failure of the composite. This value can only be found in the basic model. All other models had an MxPS-C that was greater than 100 MPa (Figure. 4). Since there are no studies with a similar scope and outcomes, comparisons were limited.

Clinical impact

The results of this study highlight the effects of changing the size and position of composite on the retainer wire. It would be a better practice to standardize the amount of composite by using molds and ensuring that the bonding site is to the center of the lingual surface of the teeth. Otherwise, the mechanical behavior of retainer wires might be altered, which will affect composite and eventually might impact the whole retention process.

Limitations

The FEA is only an approximation of the actual situation. Caution must be practiced when interpreting the findings of this study in terms of clinical practice due to the following facts:

1. The teeth were modeled with an idealized shape and position.

2. The PDL was assumed to have equal thickness all around the roots and have linear behavior, which is not the real condition.
3. The shape of the bone was an approximation of the basic cross-sectional shape of the mandible.
4. The wire was modeled with ideal geometry and dimension; in real life, there may be inaccuracies in milling the retainer wire, or the retainer wire may have some notches or scratches that will affect its mechanical performance.

CONCLUSIONS

Within the limitations of this study, bonding PEEK wires with 4 mm bonding spots to the clinical crown center provided the best mechanical performance of the wires and spots; otherwise, the mechanical properties of the wire and composite would be affected and, therefore, the retention process.

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Conflicts of interest

The authors has nothing to disclose.

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الخلاصة

الخلفية: تم استعمال مادة البولي-ايثر-ايثر-كيتون (البيك) في العديد من مجالات طب الأسنان. وقد تم مؤخرا اختبارها مثبتاً للأسنان بعد اكمال علاج تقويم الأسنان. تهدف هذه الدراسة إلى تقييم تأثير تغيير حجم وموقع الروابط الراتنجية على أداء أسلاك التثبيت من البيك.

المواد وطرق العمل :تم إجراء دراسة ميكانيكية-حيوية تضمنت أربع تصاميم ثلاثية الأبعاد للعناصر المحددة. التصميم الأساس تضمن سلكا من البيك ذو مقطع دائري بقطر 0.8 ملم، مثبت إلى وسط السطح اللساني لتاج الأسنان الأمامية السفلى باستعمال روابط راتنجية بقطر 4 ملم. تم تصميم نموذجين بحجم روابط راتنجية 3 و 5 ملم. في حين تم تصميم النموذج الأخير بتغيير موقع الرابط الراتنجي على الناب بعيدا عن وسط السن باتجاه للقاطع الجانبي. تم تقييم الانحرافات الخطية في الاسنان، والشد في النسيج الرابط حول السني، والاجهادات في سلك البيك والروابط الراتنجية.من خلال برنامج التحليل، تم توليد البيانات وعرضها بترميز لوني. تم جدولة قيم بيانات مختارة ومقارنتها بين التصاميم المختلفة.

النتائج:كان مقدار الانحرافات الخطية صغيرا جدا. تأثرت الاجهادات في السلك والروابط الراتنجية بتغيير حجم وموقع هذه الروابط. تم تحديد حدود الأمان بـ 235 ميكا باسكال لمادة البيك و 100 ميكا باسكال لمادة اللاصق الراتنجي. في التصميم الاساس، كانت قيم إجهاد فون ميسز في سلك البيك مساوية لـ 122.09 ميكا باسكال، والاجهاد الاقصى الرئيسي في اللواصق الراتنجية 99.779 ميكا باسكال، ويقع كلاهما ضمن حدود الأمان للمادتين، مما يعني انخفاض مستوى خطورة فشل السلك والرابط الراتنجي في هذا التصميم. تجاوزت مستويات الاجهاد في التصاميم المتبقية حدود الأمان للروابط الراتنجية. التصميم ذو حجم روابط 3 مليمات كان الوحيد الذي تجاوزت فيه قيم الاجهادات حدود الأمان لأسلاك البيك.*

الاستنتاجات: مع الاخذ بنظر الاعتبار العوامل المحددة لهذه الدراسة فإن تثبيت أسلاك البيك إلى وسط السن باستعمال روابط راتنجية بقطر 4 ملم يوفر الاداء الميكانيكي الأفضل للأسلاك وللروابط، بخلافه فإن الخصائص الميكانيكية للأسلاك والروابط سوف تتأثر مما يعني التأثير على عملية التثبيت برمتها.

الكلمات المفتاحية: التثبيت، البيك، تحليل العناصر المحددة.