Stress distribution in ceramic orthodontic bracket, tooth, bone and PDL contact assembly - A finite element study

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Abstract. Malocclusion (teeth irregularity) problems are increasing rapidly across the world in all age groups. Malocclusion is treated in orthodontics which is a specialty of dentistry. Orthodontic bracket is a component of fixed orthodontic appliance which is used to treat the malocclusion through archwire forces transferred to the tooth. In orthodontic treatment, the preadjusted orthodontic brackets are most widely used compared to the conventional brackets as there is an in-built torque by the angulated slot walls. This study aim to compare the stress distribution in the preadjusted ceramic brackets with and without Stainless steel (SS) metal slot insert along with tooth, alveolar bone and Periodontal Ligament (PDL) contact assembly using Finite Element Analysis (FEA). A preadjusted maxillary right central incisor ceramic orthodontic bracket (with and without metal insert in the slot) are modeled using CATIA software. The solid model of a maxillary right central incisor tooth is obtained from a Computer Tomography (CT) scan using image processing software. The PDL and alveolar bone are modelled using CATIA as per the dimensions. The assembled solid model consists of bracket with and without SS metal slot insert, adhesive layer, tooth, alveolar bone and PDL. The contact between the components and the mesh is created using hypermesh software. The archwire torque is applied as couple inside the bracket slot without using an archwire. The stress distribution in the assembly components are analysed for the applied couple (torque). The stresses induced in the assembly components are compared between ceramic bracket with and without metal slot insert. This in-silico study would help the clinicians to understand the behavior of commonly used ceramic bracket with and without metal slot insert and choose the appropriate bracket for successful treatment.

1. Introduction
Adults and adolescents are giving more concern to facial esthetics irrespective of the age group. Orthodontics is the speciality of dentistry which deals with malocclusions, treating teeth irregularity. Orthodontic treatment aims to correct the malocclusion problem by aligning the teeth in maxillary and mandibular jaws. The orthodontic bracket, archwire and ligature are the main components of fixed appliances used to position the teeth, which are working with mechanical principles. Generally, the archwire which is entrapped inside the bracket slot is held in place by the ligatures. After moderate teeth alignment, torque is applied in the rectangular archwires which generate forces in the bracket. The generated force is transferred to the teeth through the bracket which is bonded on the teeth enamel surface using a bonding material termed as the adhesive layer. The application of archwire force
produces stresses on the teeth, PDL and its adjacent bony structure namely the alveolar bone. Various types of brackets, archwire materials and ligatures are used during the treatment. The terms couple, moment, torque are alternatively used in orthodontics. The ceramic brackets are preferred by patients due to its tooth color. Ceramic brackets are nickel free hence it does not create allergy problems to the patients. The disadvantage in ceramic brackets is that the slot wear and tear is more due to the metallic archwire friction. To overcome this slot damage, ceramic brackets are also manufactured with a SS slot insert. It is complex to use the experimental techniques to predict the behaviour of tooth, alveolar bone, PDL with bracket and adhesive layer. Hence, the FEA studies are widely used in orthodontics to predict the stress concentration and distribution in the fixed appliances components.

Poiate et al. [1], did a FEA of PDL with a maxillary central incisor to predict its behaviour in different loads and stated that the function of PDL is to be studied well to understand it better. Fongsamoot and Suttakul [2], studied the stress distribution in tooth with the presence and absence of PDL using FEA. In this study, the orthodontic bracket was not considered. Cai et al. [3], studied the stress and displacement of canine tooth with PDL considering rotation, inclination and translation. The stress and displacement variations are noted in different tooth movement. Panagioutopoulou et al. [4], did an FEA and stated that the strain is distributed locally to the alveolar bone by PDL, which does not have effects on other places of the mandible. Papageorgiou et al. [5], studied the effects of components of fixed appliances by varying the materials using FEA. It is suggested that all the components influences the tooth movement. Harikrishnan et al. [6], studied the deformation in SS and ceramic bracket slot due to the application of archwire torque using FEA. Ghosh et al. [7], analysed the distribution of stress in different brands of ceramic brackets without considering the tooth, alveolar bone and PDL. Thus, this study is designed to compare the stress distribution in the preadjusted ceramic bracket with and without SS metal slot insert along with the tooth, PDL and alveolar bone contact assembly using FEA.

2. Materials and methods

This study is carried out to demonstrate the effect of metal slot insert in ceramic bracket. The dimensions of a 0.558 mm × 0.711 mm ceramic preadjusted right central maxillary incisor bracket (Ormco roth™, USA) is measured using an optical profile projector (ph3500-Mitutoyo®, Japan). The profile points of the bracket is captured with 10x magnification. The captured profile points are imported to the drafting software (AutoCAD). From the obtained bracket dimensions through AutoCAD, a 3D model of the bracket is constructed using a software (CATIA®). The 3D model of a maxillary central incisor is obtained by image processing from a CT scan of the upper jaw (adult male patient) and CATIA. The 3D model of the bracket and maxillary central incisor is shown in Figure 1 (a) and (b). The PDL of 0.2mm thickness is modelled by covering the root of the tooth. The alveolar bone of cylindrical shape with 5 mm wall thickness is modelled. The 3D model of the PDL, tooth and alveolar bone are assembled. In this study, the modelled bracket is assembled on the tooth enamel surface with 0.5 mm thickness adhesive layer. The assembled model of all the components is shown in Figure 2. In this study, the ceramic bracket is considered with and without SS slot insert. The thickness of SS metal slot insert is 0.1 mm.
The archwire is not considered in this study. The assembled model is meshed using the software HyperMesh®. The isoparametric tetrahedral solid 185 element is used to mesh all the components. The total number of elements used for meshing is presented in Table 1. Figure 3 (a) shows the meshed assembly. The contact between PDL and alveolar bone is constructed. Similarly, the contact between bracket base with adhesive layer, labial surface of tooth with adhesive layer is established. Figure 3 (b) shows the meshed ceramic bracket with metal slot insert.

| Name of the component | Number of elements |
|-----------------------|--------------------|
| Bracket               | 39573              |
| Tooth                 | 30459              |
| PDL                   | 10141              |
| Alveolar bone         | 10571              |
| Adhesive layer        | 4834               |

**Figure 2.** Assembled model of Tooth-adhesive layer.

**Figure 1.** 3D Model.
Figure 3. Meshed model.

The meshed assembly is imported to the software for analysis (Ansys). The boundary conditions are as follows: all degree of freedom (DOF) on the top surface of alveolar bone is arrested. The nodes in the bracket base is fixed with tooth through adhesive layer. The range of torque transferred to maxillary central incisor is 10.35 Nmm to 23.73 Nmm [8]. In this study 17 Nmm torque (T) only is considered and converted as couple considering the perpendicular distance (D = 0.6 mm) between archwire contact points in the gingival and occlusal side slot walls. The obtained force (F = T/D) of 28.3 N is applied as couple in slot walls without using archwire, but in the contact areas as simulated in an archwire-slot contact. The mechanical properties of the components are obtained from the literatures and are presented in Table 2. [9-12]. The couple of 28.3 N is applied as palatal root torque as shown in Figure 4. The stress and displacement in the assembled components are obtained.

Table 2. Mechanical properties of the components

| Components                      | Young’s modulus (N/mm²) | Poisson’s ratio |
|---------------------------------|-------------------------|-----------------|
| Bracket (ceramic)               | $3.79 \times 10^5$      | 0.29            |
| Slot insert (SS)                | $2 \times 10^5$         | 0.30            |
| Tooth                           | $2 \times 10^4$         | 0.3             |
| PDL                             | 1.0                     | 0.45            |
| Alveolar bone                   | $2 \times 10^3$         | 0.3             |
| Adhesive layer (composite resin)| 8823                    | 0.25            |
3. Results and discussion
Torque is vital for refining tooth movement. Due to the application of archwire torque in the bracket slot, stress is induced in the bracket, adhesive layer, tooth, PDL and alveolar bone. In this analysis, the distribution of stresses are obtained in all the components. In particular, the variation of stress between ceramic bracket with and without SS slot insert is compared along with other biological components. The comparison of generated stress in all the components with and without SS slot insert in ceramic bracket is presented in Table 3.

Table 3. Comparison of stresses in the components with and without SS slot insert in ceramic brackets

| Component     | Stress (N/mm²) | Without SS slot insert | With SS slot insert |
|---------------|----------------|------------------------|---------------------|
| Bracket       | 250.82         | 200.62                 |                     |
| Alveolar bone | 0.194          | 0.189                  |                     |
| PDL           | 0.021          | 0.018                  |                     |
| Tooth         | 2.724          | 2.487                  |                     |

The stress distribution in ceramic bracket with and without SS slot insert for the application of 28.3 N force (17 Nmm torque) is shown in Figure 5 (a) and (b). The stress concentration is more in the junction of slot wall and slot base. The stress in ceramic bracket with SS slot insert is lesser than without SS insert. Generally, ceramic brackets do not withstand the pressure generated by the metal archwires and also bracket slot is subjected to friction when the archwire is activated. Hence, ceramic bracket is not ideal when the extensive treatment period is needed. This study results showed that when the SS insert is embedded into the ceramic bracket slot, the stress distribution is reduced in the bracket and in the other biological components as shown in Figure 6 a, b, c and d. Jena et al. [13] stated that the ceramic bracket strength is increased due to the SS slot insert when the archwire is activated. Rudolph et al. [14] found that the magnitude of stress in alveolar bone is more than that of PDL. Similarly, our result showed that the stress in alveolar bone is greater than PDL in both brackets with and without SS slot insert. It is stated that the PDL is compressed to 0.0196 N/mm² during orthodontic forces [15, 16]. In our study, the stress acting on PDL is 0.018 N/ mm² and 0.021 N/mm² in bracket with and without SS slot insert respectively.
**Figure 5.** Stress distribution.

(a) in bracket without SS slot insert.  
(b) In bracket with SS slot insert.

**Figure 6.** Comparison of stress in the components with and without SS slot insert in ceramic bracket.

(a) Bracket  
(b) Alveolar bone  
(c) PDL  
(d) Tooth
In our study, the obtained stress is 250.82 N/mm² and 200.62 N/mm² in bracket with and without SS slot insert respectively. Similar to our results, Ghosh et al., [13] found using FEA, the stress in different brands of ceramic bracket ranged between 115 N/mm² to 468 N/mm². The increasing order of stress in the biological components are in PDL, alveolar bone and tooth. Similar increasing order of stress was showed by Jing Yan et al. [17]. In this study, the displacement of tooth and PDL ranged from 0.01 mm to 0.02 mm. Jones et al. [18] determined that the displacement of tooth and PDL is ranged from 0.012 mm to 0.133 mm.

This study results clearly indicates that the stress induced in ceramic bracket with SS slot insert and its associated biological components are lesser than that of ceramic bracket without SS slot insert. It is always preferred to reduce the stress distribution to avoid the slot damage in the bracket during the treatment when the archwires are activated. The SS slot is inserted to strengthen the ceramic bracket. However, it is observed that some amount of applied force in bracket slot is taken by the SS slot insert. Hence, the force transferred to the tooth might be reduced. For the same torque magnitude (17 Nmm), the bracket with SS slot insert showed lesser tooth movement (0.025 mm) than bracket without SS slot insert (0.027 mm). Clinically, this variation in tooth movement is to be considered between the brackets with and without SS slot insert for appropriate force application by the orthodontist. This study provides enough evidence to the clinicians to understand the behaviour of ceramic bracket with and without SS slot inert and may help to choose the appropriate bracket and force for successful treatment.

4. Conclusion
In this in-silico study, the stress distribution in ceramic bracket (with and without SS slot insert) with adhesive and biological components are studied. It is concluded that the ceramic bracket with SS slot insert is producing less stress in the bracket and its adjacent biological components compared with ceramic bracket without SS slot insert. But, the tooth movement is lesser in ceramic bracket with SS slot insert when compared with bracket without SS slot insert. This study clearly demonstrated the effect of SS slot insert in commonly used ceramic bracket with Thus, we conclude that the SS slot insert in ceramic brackets reduce the stress in the bracket and the biological components assembly.

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