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Physiological Response of a Natural Central Incisor Tooth to Various Loading Conditions: A 3D Finite Element Study

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Abstract

This study evaluates the influence of different loading angles and the area of loading on the ensuing stress distribution and the physical response of a natural central incisor tooth, using a 3D finite element analysis. The CAD model of the incisor tooth assembly (including enamel, dentin, periodontal ligament, pulp, gingiva and jaw bone) was subject to an external (chewing) load of 100 N, over four different areas and at four different angles along the vertical. It was observed that the tooth experiences high von-Mises equivalent stresses and high bending when the load applied is closer to the incisal edge of the crown. Also, the stresses on the dentin, in general, increased with the increase in the loading angle regardless of the area of loading; with the highest stress (~70 MPa) generated at 45° angle. The percentage change observed in dentin von-Mises stresses was higher than that of enamel when the loading angle was increased from 0° to 45°, because of the higher stiffness of enamel and structural differences in enamel and dentin. The numerical results indicated that applying loads on incisal edge would simulate a severe loading condition for the incisor tooth.

Keywords

Dental materials; finite element analysis; incisor tooth; stress analysis

1. Introduction

Clearly, teeth are an important part of human body playing an important role in our digestive systems by grinding the food to swallowable size [1, 2]. Approximately half of the population experience tooth loss at some stage in life due to various factors, excluding the natural loss due to age [3-7]. The loss of teeth due to unnatural causes is often treated with artificial teeth which have life expectancy of 65-95% [8-12]. This range excludes the frequent failures of the crowns due to cracking and chipping. Such high failure rate can be associated with the lack of understanding of natural tooth structure and its behaviour under external loading. The artificial crowns are designed to have physical material properties similar or higher than those of the natural enamel, the hardest and stiffest material in the human body, unlike a multi-layered multi-stiffness natural tooth [13-24]. One of the periodontal ligamental connects the tooth to the mandibular bone and helps tooth movement [25].

In order to design a replacement for any biological structure, it is important to understand the original structure - in this case, the natural tooth. Use of FEA (finite element analysis) is common in engineering to design new parts and to understand the physical response of material structures to external loading. Similarly, in dentistry, researchers have used FEA to analyze artificial teeth and compare different design parameters, including variation in restorative materials, loading direction and geometry of the tooth [13, 16, 18, 20, 26-54]. Another recent study on glass fiber restorative implant material showed that even the reinforcing fiber orientation can significantly influence the stress pattern in the teeth [55]. With this multitude of design variables, it is of importance to first understand what are the most serve mechanical loading conditions (loading patterns targeted, area of loading applied, along with other boundary conditions) on the behaviour of natural tooth itself, based on which then the design and analysis of artificial teeth can be optimized [53].

2. Objective, Materials and Methods

Here, using FEA, an attempt has been made to assess the effect of different loading conditions on ensuing von-Misses stresses in a natural central incisor tooth, thereby providing a more holistic understanding of the physical behaviour of such structure and exploring a sever loading case that may be used for future numerical studies. A total of 16 loading cases are simulated and compared based on the location and angle of the applied (chewing) load.

2.1 3D Geometry

For the natural tooth geometry, a readily available incisor CAD model, also developed from scans, was employed from grabcad.com [54-58]. The base model was modified to have multiple layers such as pulp chamber, periodontal ligament, dentin and the enamel as shown in Figure 1. The layer thicknesses were maintained as per the ranges specified in the study [59]. This sub-structure was then assembled on bone CAD model created with two layers – cortical and cancellous bone (Figure 1). The CAD models were created in SolidWorks and were imported into ANSYS Mechanical 16.0, meshed with SOLID 187 element type, created with hex dominant shape. The areas expected to be structurally susceptible to stresses such as incisal edge, fillets, thin cross-section and rounds were re-meshed with finer element sizes, with an average total skewness factor of 0.36, and the highest body element size of 1 mm. Meshing resulted in 562,425 elements and 1,881,588 nodes. All the contacts were of bonded type.

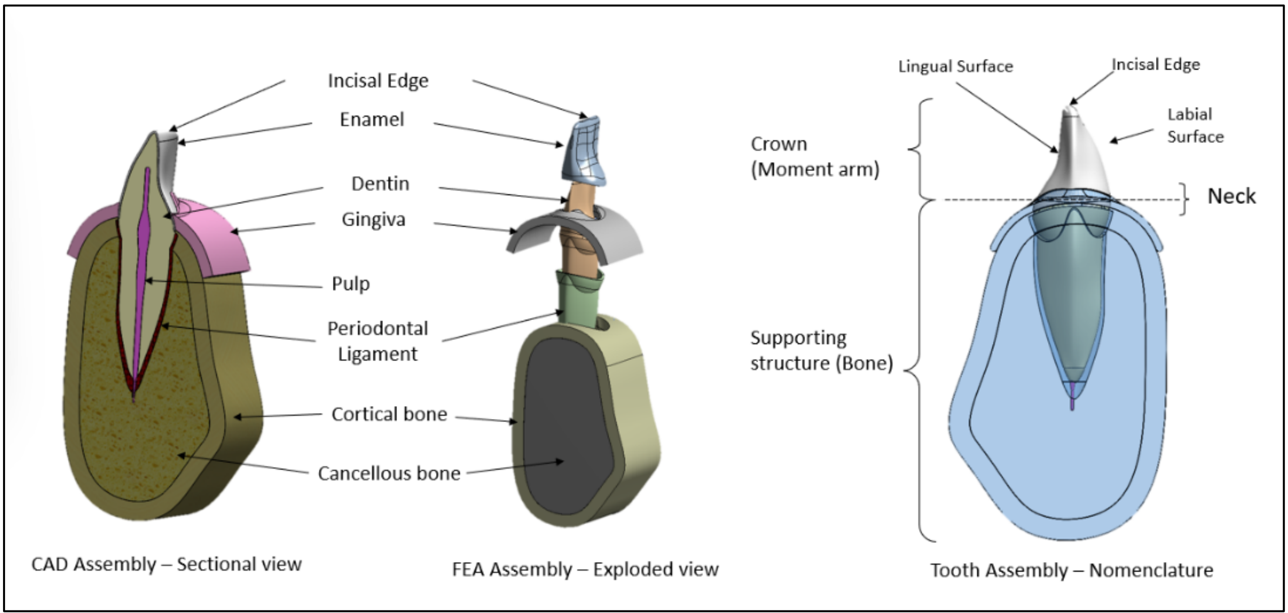

Figure 1 Natural tooth internal layered structure and tooth assembly with the supporting structure and pictorial distinction of crown and neck.

2.2 Material Properties, Loading and Boundary Conditions

Table 1 shows the mechanical properties considered for this study. Due to variation of the loading conditions in the previous FEA studies [56] and to find the most severe loading condition for an incisor, the crown was subject to a uniformly distributed load of 100 N applied over four loading surfaces at four different angles (0°, 15°, 30°, and 45°) with respect to the tooth vertical axis (Figure 2). Each loading case was evaluated separately. The side faces of the bone were fixed in all directions (6DOF) as shown in Figure 2.

Table 1 Material properties considered for the analysis of natural tooth [59].

Sr. #	Component	Young's Modulus (GPa)	Poisson's Ratio	Layer Thickness (mm)
1	Enamel	84.1	0.3	0.2
2	Dentin	18.6	0.31	NA
3	Pulp	0.002	0.45	NA
4	Periodontal Ligament (PDL)	0.0689	0.45	0.25
5	Cortical Bone	13.7	0.3	1.5
6	Cancellous Bone	1.37	0.3	NA
7	Gingiva	0.0196	0.3	1.2

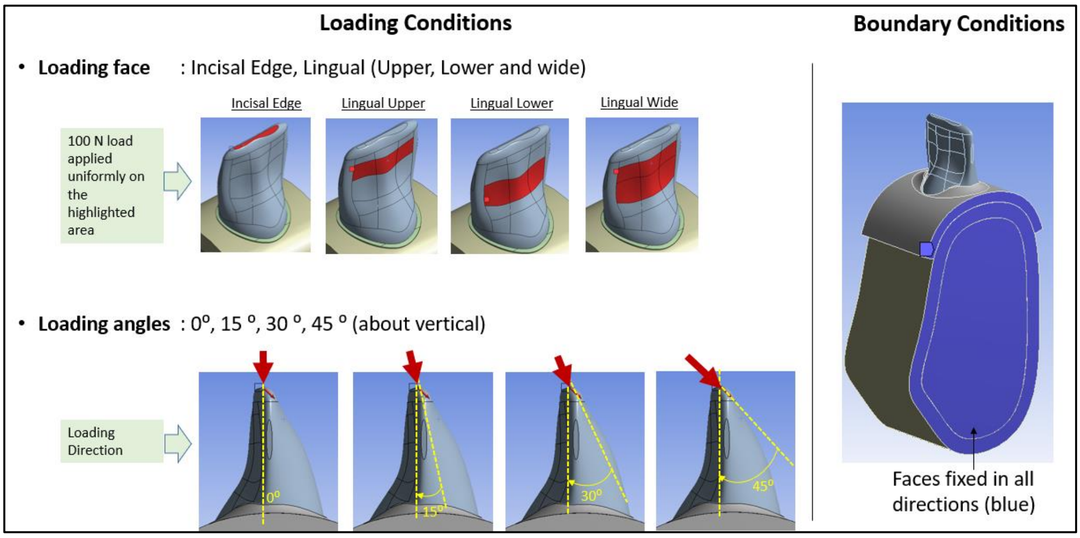

Figure 2 Design of the study: Loading and boundary conditions used for the FE analysis – four loading faces on the crown and each face subject to 100 N of uniformly distributed load at four loading angles. The side surfaces of the bones and gingiva (blue highlights) fixed in all directions [59].

3. Results

In order to understand response of the tooth to the different loading conditions and find the most severe loading condition, a total of 16 load cases were simulated, based on the combinations shown in Figure 2. The equivalent von-Mises stresses generated in the enamel and dentin were compared in Figure 3. Comparison of the stresses in enamel shows that the tooth crown experiences the highest stresses (among the cases simulated) when the load is applied on the incisal edge of the incisor tooth. A maximum stress of 150 MPa was observed in the incisal edge load [60] case followed by 113.5 MPa in upper lingual load case. An ANOVA analysis of the data [59] (with $\alpha = 0.05$) also showed that the stresses induced in the tooth are more significant to the selection of loading surface than they are to the loading angle.

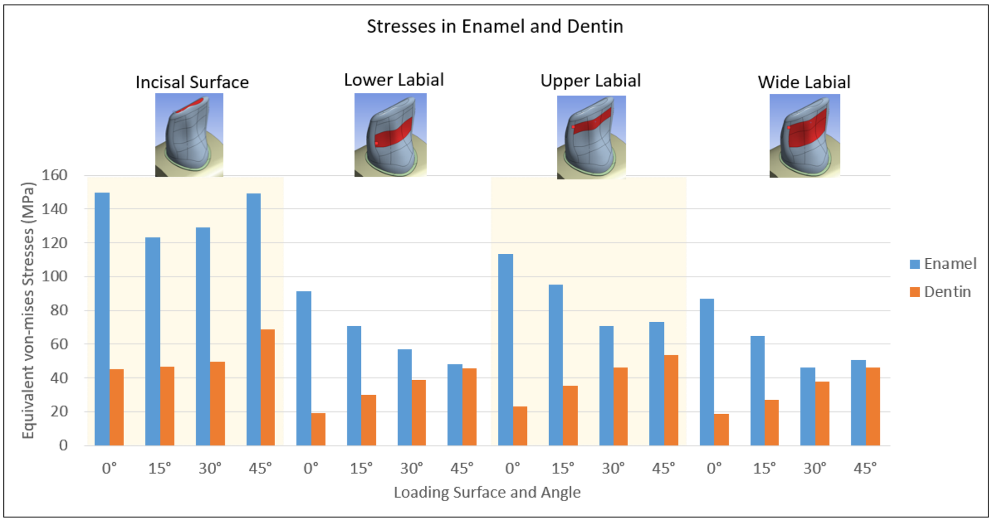

Figure 3 Natural tooth equivalent (max) von-Mises stresses in enamel and dentin for each loading case on the natural tooth.

The equivalent stress variation of the enamel with incisal edge loaded at different angles show that the high stress location gradually moves from the incisal edge to the labial surface (Figure 4). As the angle of loading increases, the tooth starts bending backwards on the labial side. The higher the loading angle, the higher the bending of structure.

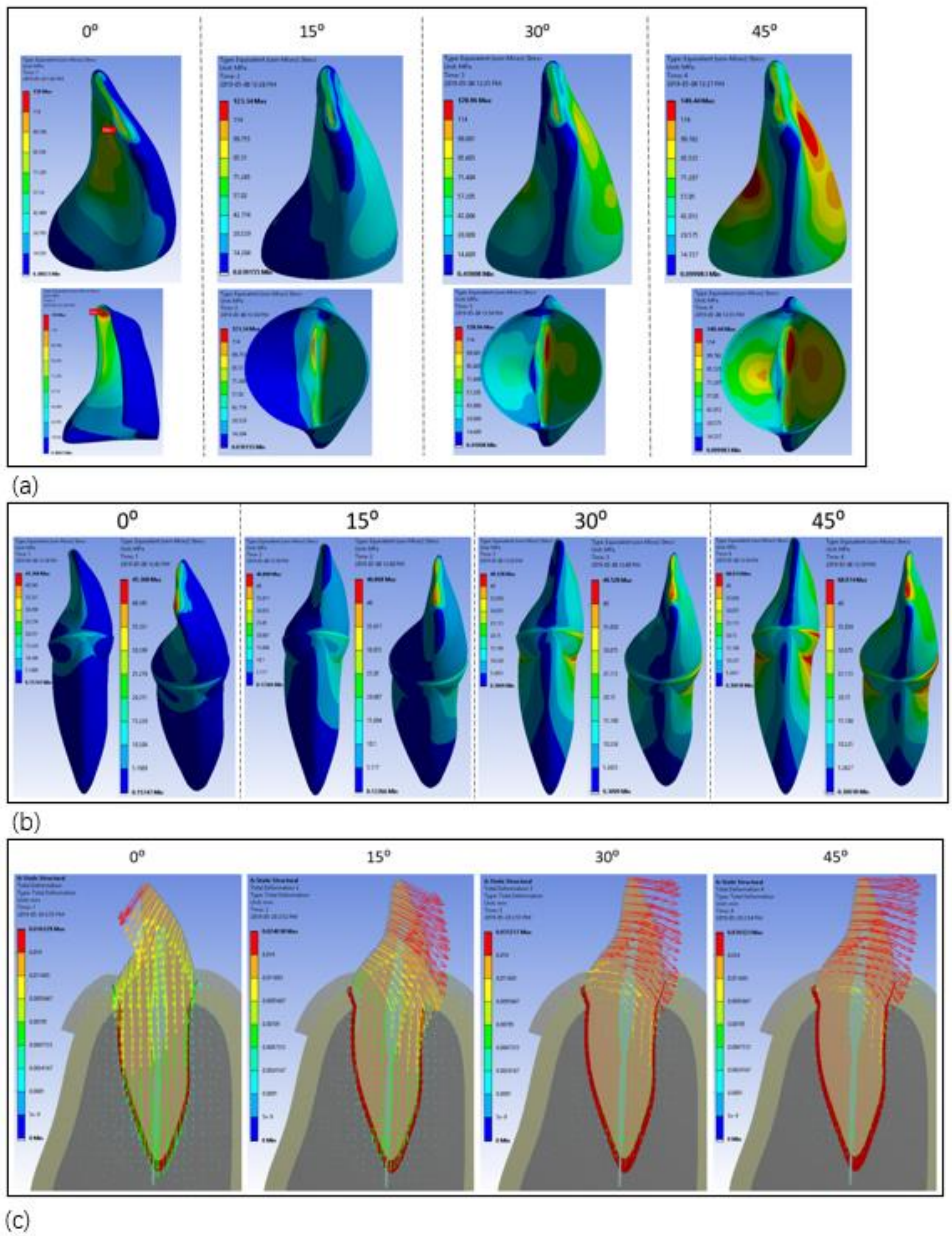

Figure 4 Equivalent stresses in (a) enamel and (b) dentin (b), for incisal edge loading case at different angles; showing an increase in the overall stresses on the labial side with increase in the loading angle. (c) displacement vector plot showing change in bending with angle of loading.

The equivalent stresses in dentin increased from 45 MPa to 69 MPa with the increase in loading angle for incisal edge case (Figure 3). Also, the high stress location moved from the tip of the dentin to the neck region with the increase in loading angle (Figure 4). Similar to the enamel, higher bending of the dentin body is observed with higher angle of loading. It was observed that the dentin body bends from the neck region when the loads are applied at higher angles thereby generating high stresses at the neck. The jaw bones follow the deformation pattern of the dentin. Per Figure 5, Cortical bone has the stresses concentrated at the neck region in contact with the dentin whereas the stresses in the cancellous bone were distributed over the large conical socket the dentin sits in. The overall stresses increased with the increase in the loading angle. The von-mises equivalent stress in cortical bone increased from 7 MPa to 19 MPa whereas von-Mises equivalent stresses in cancellous bone doubled from 4 MPa to 8 MPa. These stresses remained pretty much similar for all the loading locations.

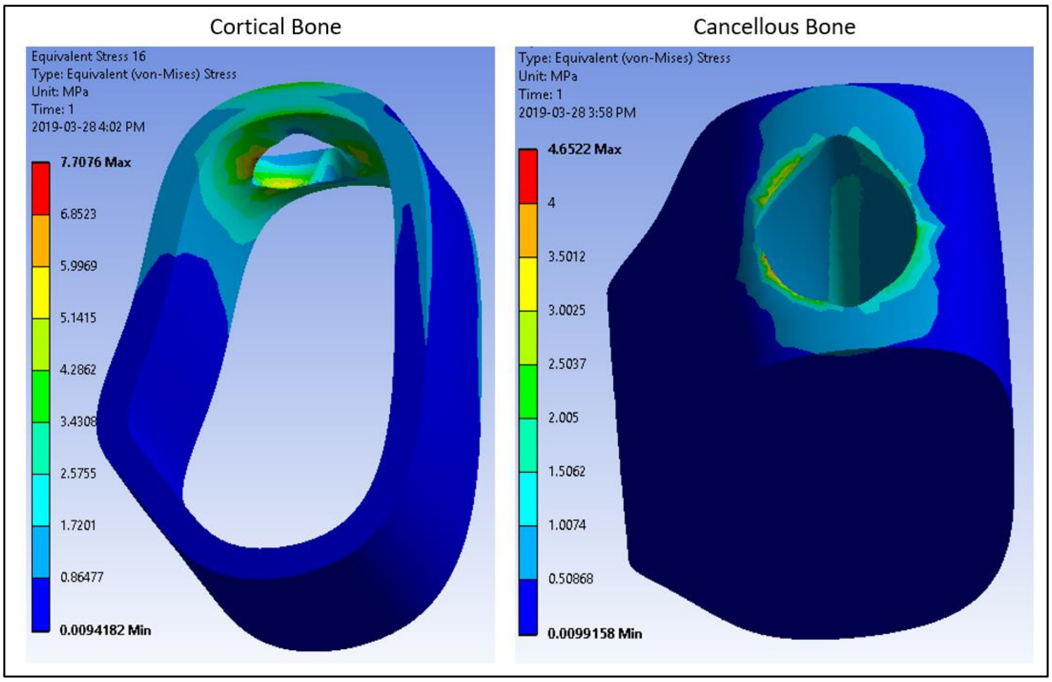

Figure 5 Equivalent stress plot of Cortical and Cancellous bones (at 0° loading on incisal edge) showing the high stress location. Cortical bone has the stresses concentrated at the neck region in contact with the dentin whereas the stresses in the cancellous bone were distributed over the large conical socket the dentin sits in; highest being on the edge.

Of note, in an auxiliary FE analysis [59], it was also observed that the addition of gingiva does not have any structural role to influence the stresses in the tooth. A case study with and without gingiva showed no difference in the stress magnitude of the tooth parts.

4. Discussions

4.1 Effect of Loading Surface

The shape of the tooth is roughly like a cylindrical magnetic needle with its one end supported by the jaw bone (Figure 1). The other end forms the visible crown, which is used for chewing the food and is exposed to external loads such as biting forces. Almost 3/5 of the tooth body is supported by jaw bones and is thickest at the neck (Figure 1). This means that the crown of the tooth behaves like a cantilever upon application of biting forces.

The increase in the stress magnitude with the increase in proximity of the loading surface to the crown tip can be easily explained by the change in thickness of the tooth along its length (Figure 6). Recalling the cross section of the tooth in Figure 6 and Figure 7, it is observed that moving from neck to the incisal edge, the area of cross section perpendicular to the lingual surface decreases. Figure 3 and Figure 6 show that with a constant load magnitude, the stresses increase as the area of cross section decreases. Hence the highest stresses are observed in the case of the incisal edge loading (150 MPa) and the next high stress value was observed in the case of the upper lingual surface loading (113.5 MPa). Following this theory, the least stress magnitude would be observed at a surface loading closest to the neck region and stress values in Figure 3 proves the same.

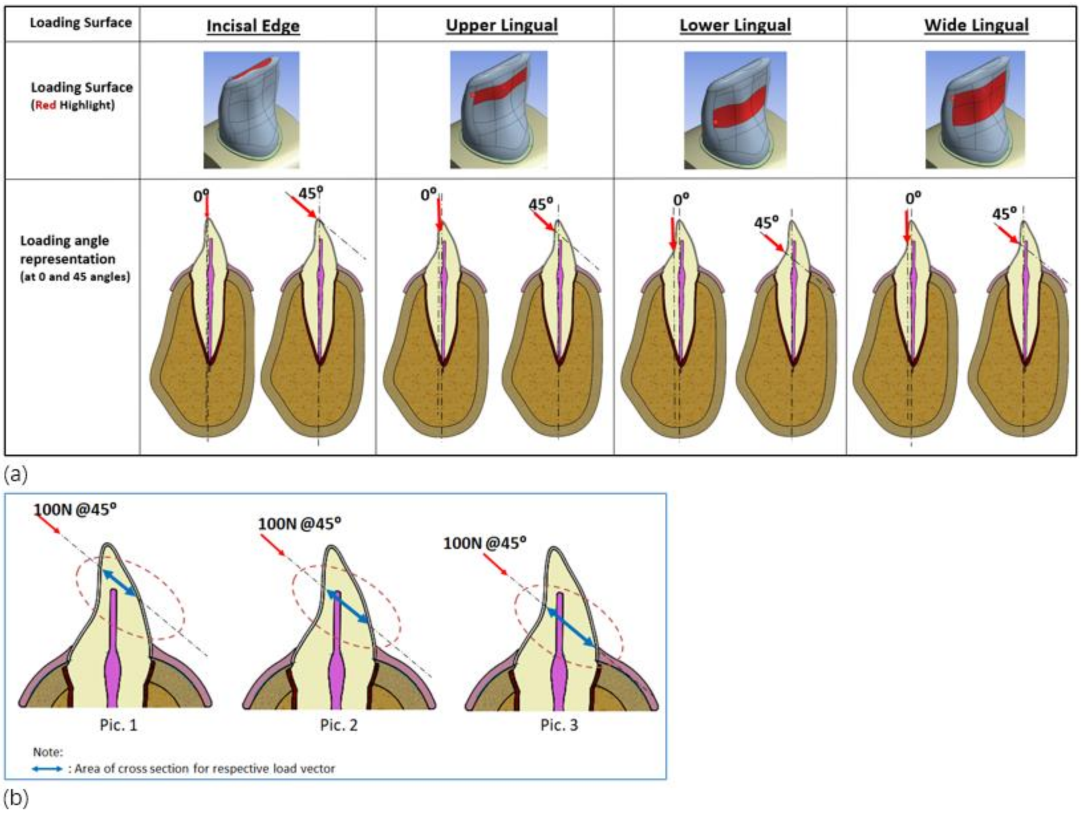

Figure 6 (a) Natural tooth loading faces and loading angles representation; Second row shows the changes in area of cross section with the change in the loading face. (b) An example of the increase in area of cross section as the loading vector lowers along tooth vertical axis. In pic-1 the loading vector is close to the narrow crown tip with certain area of cross section across the tooth thickness whereas in pic-2&3 this area increases as the loading vector axis is lowered vertically.

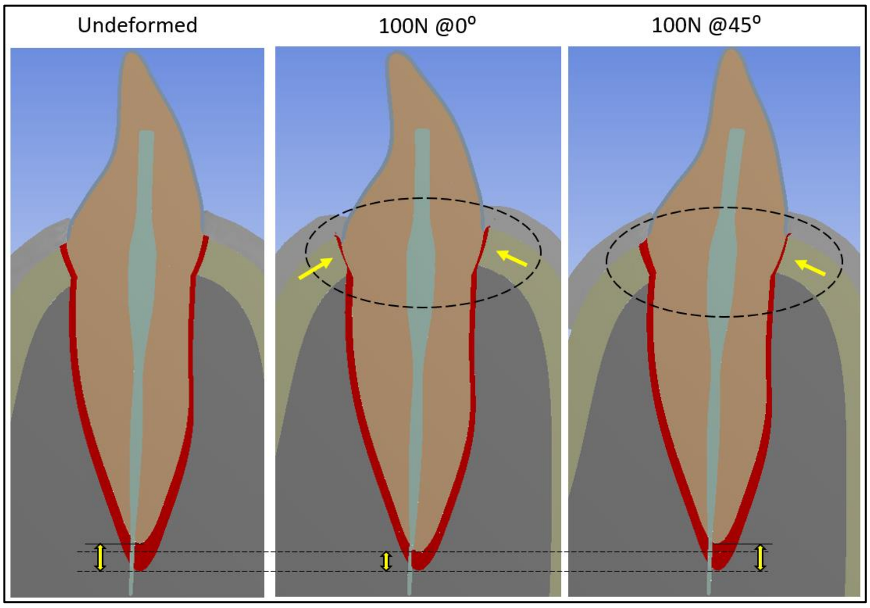

Figure 7 PDL compression at 0° and 45° loading angles in comparison with the unloaded and undeformed tooth. The PDL compression is shown by yellow arrows at the neck and at the root.

4.2 Effect of Loading Angle

As discussed in Section 4.1, the tooth crown acts like bending arm of a cantilever on application of biting forces. Theoretically, for any cantilever beam the highest bending displacement and the resulting stresses are observed when the beam tip is loaded perpendicular to the beam horizontal axis [61]. Following the same, the highest stress magnitude in dentine is observed here (Figure 3) when the loads are applied on the incisal edge at 45°. The low Young's modulus of the dentin (E = 18.6 GPa) allows it to be flexible and bend in the direction of loading, resulting into an increase in the stresses (for incisal edge loading case) from 45 MPa to 69 MPa and moving the high stress location from incisal edge to the neck (Figure 4). These observations are consistent with the study [33] which showed that the narrow structure at the crown tip causes high stresses and bending in the crown. The present numerical results also match other studies where high stresses were reported on the enamel surface within top 1/3rd region of the crown [19, 36, 45, 48].

The enamel is a thin, stiff layer (E = 84.1 GPa) on the dentin's crown. It is not directly supported by the jawbones. Hence, it follows the bending pattern defined by the dentin and show minimal change in stresses due to change in the loading angle. It is evident from Figure 3 that the percentage change in stresses in enamel is far less than that of dentin when the loading angle is changed from zero to 45° degrees.

For the jawbones, as the loading angle increases, the high stress in the dentin (Figure 3) would transfer onto the bones; resulting potentially in bone resorption [23]. However, the stress magnitude of the bone remains significantly lower than its ultimate strength [15, 62] because of the presence of a shock absorbing layer known as periodontal ligament (PDL) (Figure 1).

PDL is a layer of connective tissues between dentin and the bone. The significantly low Young's modulus (E = 0.0689 GPa) allows the PDL to compress in any direction when loaded. This property allows the tooth root to float in the bone socket. The PDL absorbs most of the loads and displacements thereby softening the blow to the bones. Results from this FEA show that when the strain in dentin was 0.0032 mm/mm the strain in the PDL had was 0.04 mm/mm. When the loads are applied in vertically downward direction, the PDL compresses at the root and allows up-down movement of the tooth (Figure 7). When the tooth is loaded at the higher loading angles such as 45°, the PDL compresses and extends along the walls to allow the tooth a fore-aft movement without damaging the supporting bones.

5. Conclusion

The performed FEA on the influence of different loading angles and the area of loading on the ensuing stress distribution of a natural incisor tooth showed that, the tooth experiences highest stresses when the loading surface is close to the incisal edge. This is because of the thin cross section at the crown tip generating high stresses. High loading angle causes the dentin to bend like a cantilever. Hence, a combination of high loading angle and incisal edge loading results in the highest stresses overall. It is important to consider the flexibility of the natural tooth system when designing the replacement artificial teeth. The variation in the Young's modulus and presence of the PDL keeps the bones protected from overloading and shock loads.

5.1 Limitations and Future Work Perspective

The scope of this study was limited to 'numerical' comparison of different loading cases for an incisor tooth, namely to explore which tooth area and which angle would serve as the most severe loading case (Figure 2). Lab- or clinical-scale experiments must be conducted to validate the numerical results, along with exploring the potential uncertainties in the performance of the teeth samples under different loading cases via a statistical analysis. The CAD models considered in this study assumed a perfect shape of the incisor tooth which might not always be the case in reality. Also, even though the use of basic FEA is common for comparing different designs and understanding the basic physical behavior of a given system, it involves assumptions on the materials, loading and boundary conditions. For instance, the real human tissues are non-linear materials unlike the linear elastic material considered in the present study.

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Author Contributions

Dipti Nikam: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft. Abbas S. Milani: Conceptualization, Resources, Supervision, Funding acquisition, Writing - review & editing.

Competing Interests

The authors have declared that no competing interests exist.

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