CHAPTER 3

Materials and Methods

3.1 Research design

This study was an analytical study.

3.2 Materials

3.2.1. Commercial maxillary models (Model-i21FE-400C; Nissin Dental Products, Kyoto, Japan) (Figure 3.1)

3.2.2. Instruments and programs

- 3D scanner (D800 3D Scanner, 3 Shape, New Jersey, USA)
- SolidWorks (Dassault Systèmes, Waltham, Mass, USA).
- Abaqus (Dassault Systèmes USA)

3.3 Methods

The steps of research methodology were shown in figure 3.2.

3.3.1. Model scanning

Commercial maxillary model was scanned with a 3-D scanner and produced the digital tooth images included left and right maxillary central and lateral incisors and canines. The commercial maxillary model was a prototype for construction of the three-dimensional tooth model according to the standard dimensions of human tooth.

3.3.2. Construction and Assembly solid modeling

Solid models, including left and right maxillary central and lateral incisors and canine, periodontal ligament (PDL), and the maxillary bone (cortical and cancellous bone), were assembled using a three-dimensional computer-aided design program (SolidWorks). (Figure 3.3) The roots were embedded in the maxillary model, which was programmed to trace the cemento-enamel junction's contour gingivally. The thickness of the cortical bone was assumed to be 1.0 mm.[13, 60] The periodontal ligament was assumed to have thickness of 0.2 mm linear thickness, as previously described in other FEM studies.[61, 62] Archwire, bracket and mini-screws are created in SolidWorks program. The brackets were simulated as attachments to the middle of clinical crown. Stainless steel arch wire has a dimension of a 0.017x0.025-in, and it was assumed that no play between the brackets and the arch wire. The mini-screw position was 8 mm apical to the CEJ of the central incisors that was the recommended height.[15] In anchorage design 1, one mini-screw was placed between the roots of central incisors and in anchorage design 2, two mini-screws were placed between the roots of lateral incisor and canine, left and right. (Figure 3.4)

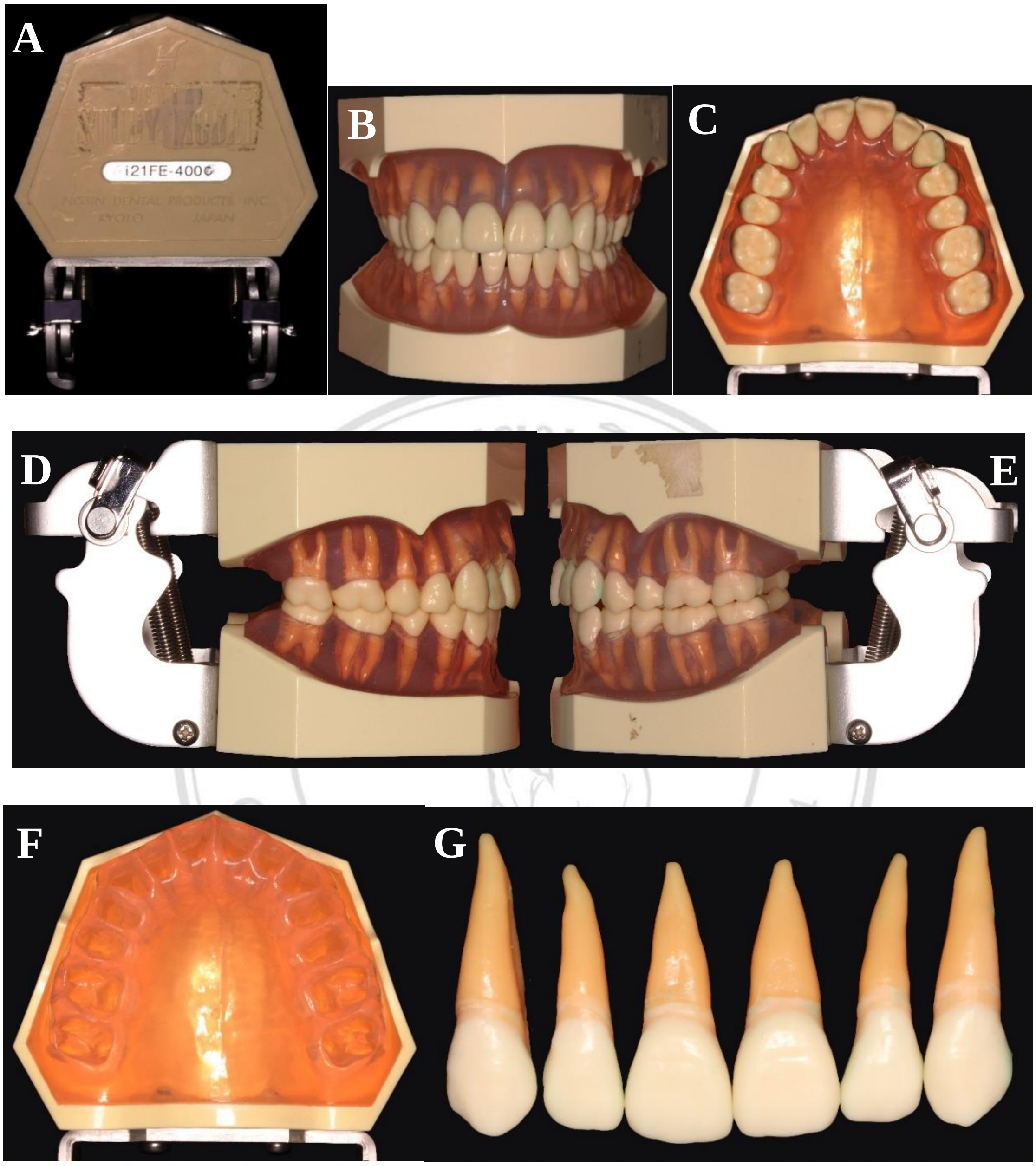

Figure 3.1 The commercial maxillary model that was the prototype for the FE model in this study. This model has teeth with all anatomical root that can remove from the socket. A) Product number, B) Frontal view, C) Occlusal view of the upper arch, D) Right view, E) Left view, F) Occlusal view when remove all of the teeth, G) Six maxillary anterior teeth with root form.

A. Model scanning

(Instrument: D800 3D Scanner)

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B. Construction and assembly solid modeling

(Software: SolidWorks)

- Design of solid model

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C. FE model construction and analysis

(Software: Abaqus)

- Discretization (meshing)
- Orientation of the model
- Definition of boundary conditions
- Assignment of material properties
- Definition of loading conditions
- Assignment of material properties

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F. Result and analysis

- Distribution of von Mises stress
- Displacement

Figure 3.2 Flow Chart of Research Methodology

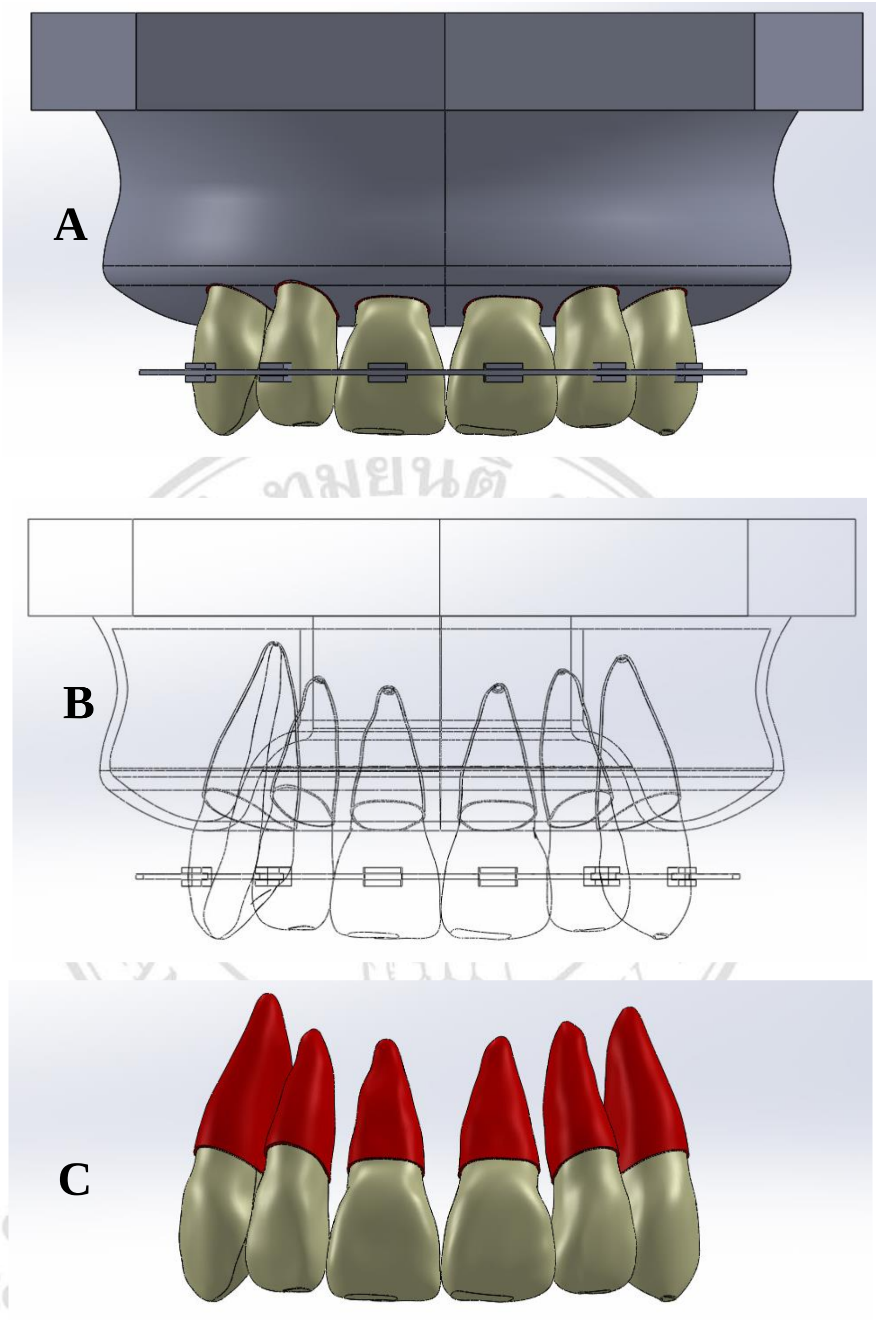


Figure 3.3 Solid model constructed from the scanning commercial maxillary model and add other component; PDL, cortical bone, cancellous bone, bracket and arch wire. A) All component assembled together, B) Transparent view of the model, C) Teeth with PDL.

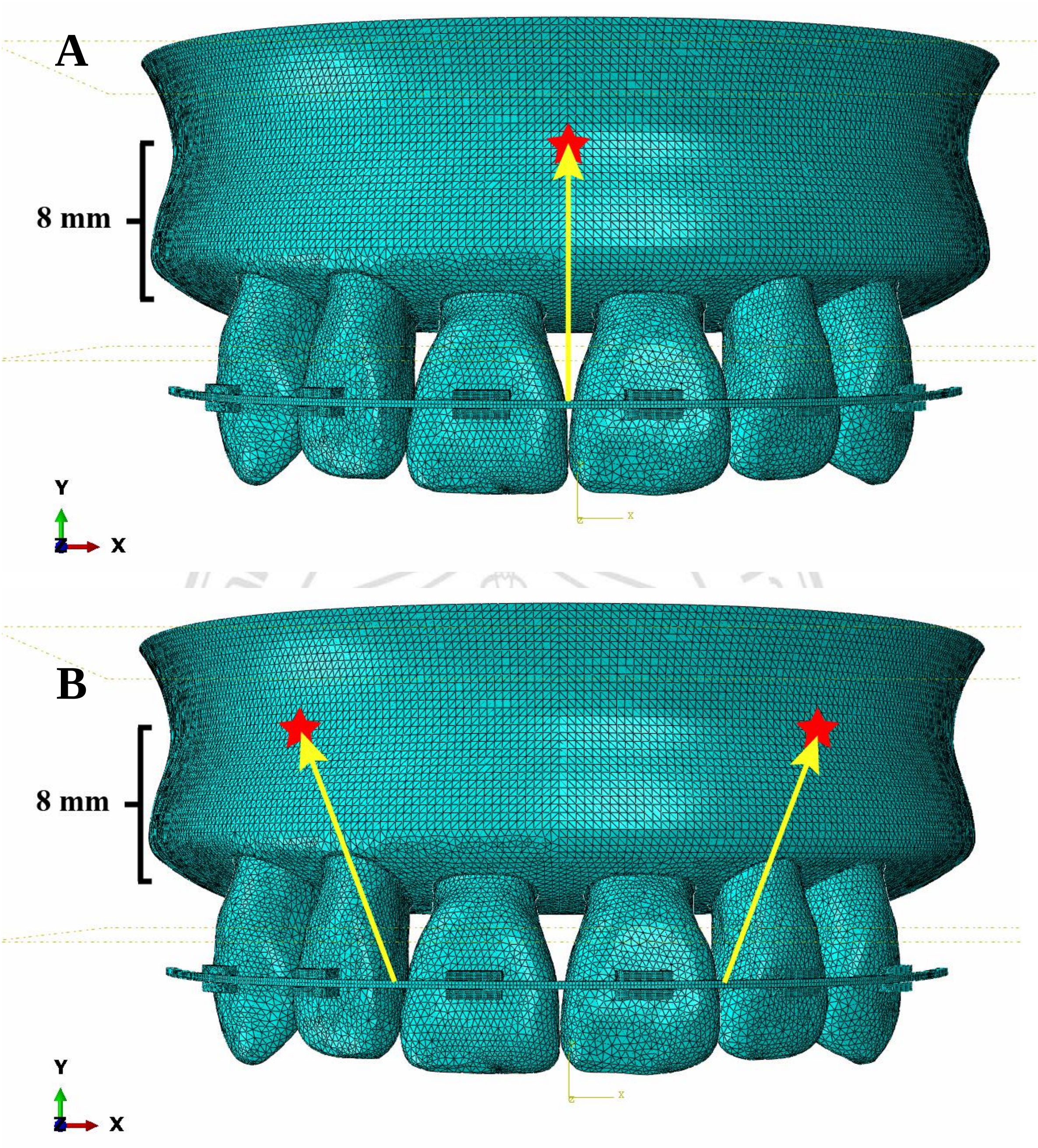


Figure 3.4 Mini-screw position (stars) and force direction (yellow arrows) A) Anchorage design 1 (one-mini-screw design), B) Anchorage design 2 (two-mini-screws design)

3.3.3. Finite element model construction and analysis

1. Discretization (meshing)

Following construction of the solid model, the model was imported into Abaqus program. The assembly model of six maxillary anterior teeth with alveolar support was meshed into several small elements. (figure 3.5.) The number of nodes and elements was shown in table 3.1.

Table 3.1 Number of nodes and elements of each component.

Part		**Node**	**Element**	**Part**		**Node**	**Element**
Tooth	11	11,103	56,884	Bracket	11	7,953	6,528
Tooth	12	9,899	50,148	Bracket	12	6,875	5,664
Tooth	13	9,816	49,542	Bracket	13	30,896	20,006
Tooth	21	10,825	55,419	Bracket	21	7,755	6,336
Tooth	22	9,214	46,527	Bracket	22	6,800	5,592
Tooth	23	10,623	54,518	Bracket	23	4,669	3,556
PDL	11	77,478	333,287	cortical		113,700	613,728
PDL	12	69,740	298,521	cancellous		60,277	255,960
PDL	13	81,605	337,826	wire		5,364	2,832
PDL	21	85,244	368,304				
PDL	22	91,504	399,876				
PDL	23	81,647	341,790	**Summary**		792,987	3,312,844

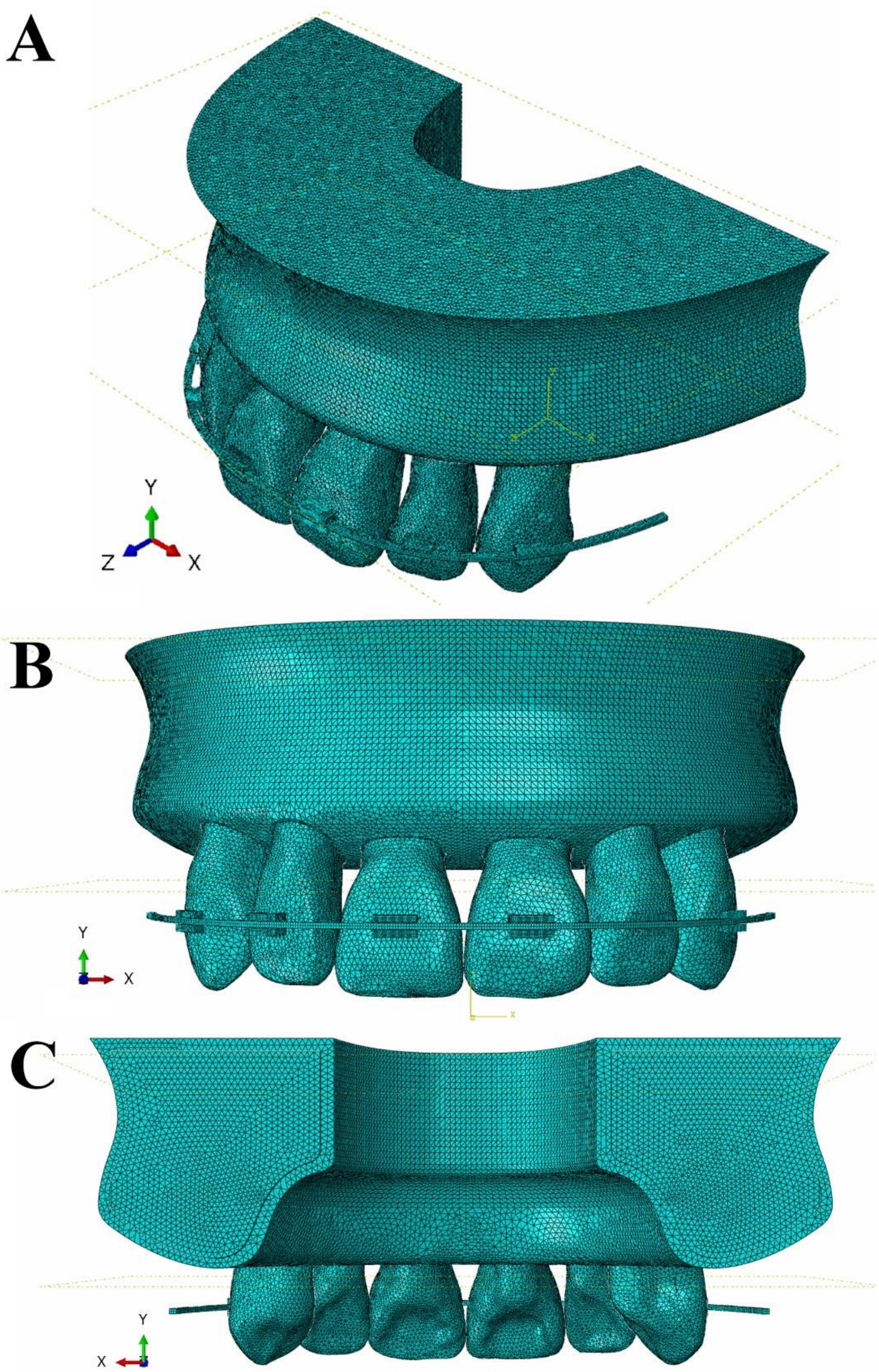


Figure 3.5 The FE model was meshed into several small elements and nodes.

A) Overall, B) Frontal and C) Back views.

2. Orientation of the models

In this model the x-axis represented the mesio-distal, the y-axis the occluso-gingival, and the z-axis the labio-palatal aspects. Reference planes: x, left; -x, right; y, superior; -y, inferior; z, labial; -z, palatal directions. (Figure 3.6)

3. Definition of boundary conditions

The boundary conditions in this study defined at the peripheral nodes of bone at the upper and back sides with no movement (zero degree of freedom) in any direction to prevent displacements from loading. (Figure 3.6)

4. Assignment of contact conditions

The nodes of the parts of the model that contacted, wire-to-bracket, bracket-to-tooth, tooth-to-PDL, PDL-to-bone, cancellous bone-to-cortical bone, were assigned the contact conditions. All contacts in this study were assigned to be tie contacts. The tie contact defined that two nodes with this contact do not separate from each other. Between teeth were an only area that assigned no contact.

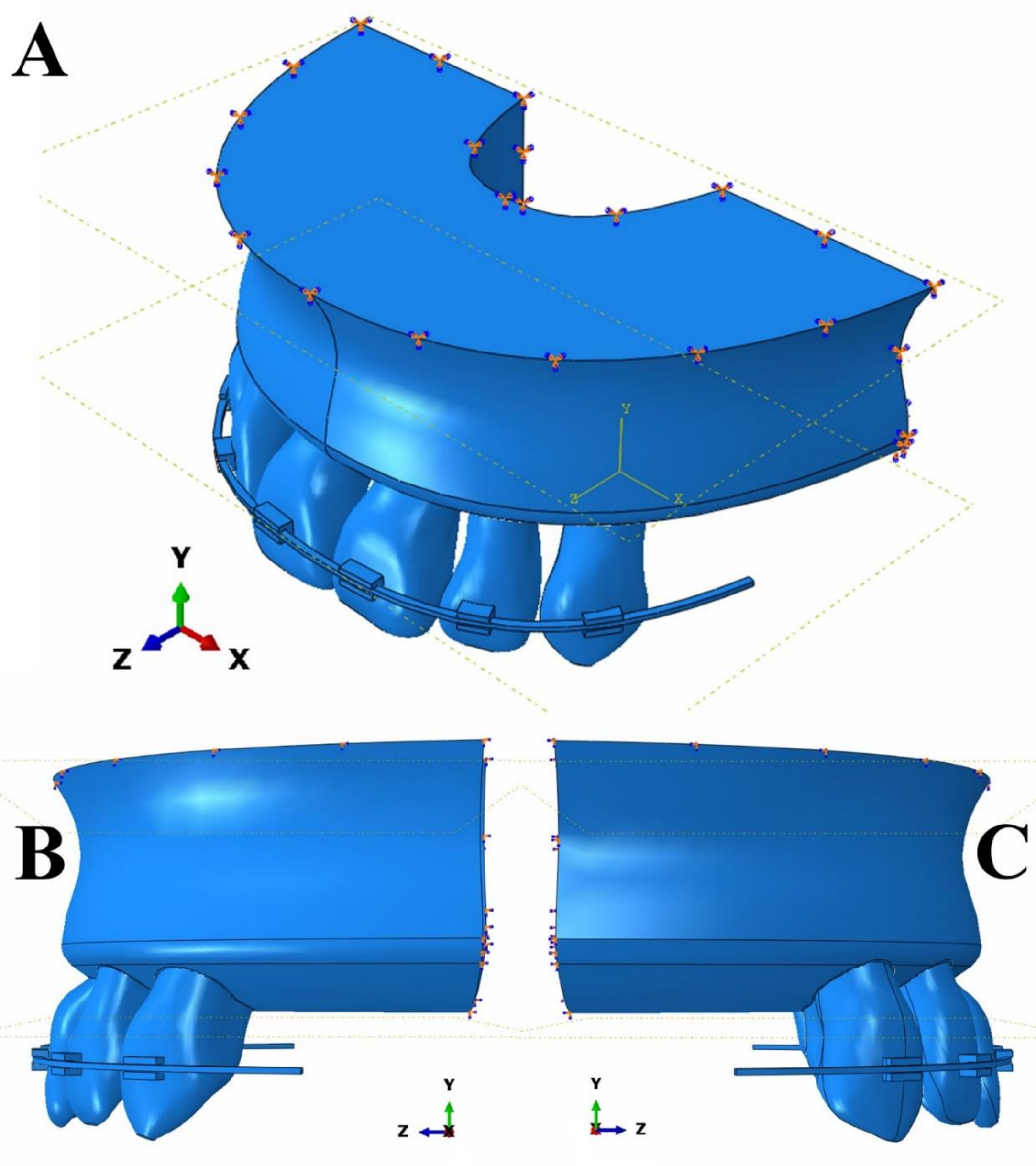


Figure 3.6 The orientation of the model and the boundary condition (orange arrows). The periphery nodes of bone of the upper and back would be defined with no movement in any direction. A) Overall, B) Left and C) Right views.

5. Assignment of material properties

The material properties, the Young's modulus (1) and Poisson's ratio (2), for dentin, bone and stainless steel were taken from the previous FE study(59) (Table 3.2). The Ogden models (3) was assigned for the PDL, non-linear elastic property. Its values were from the study of Huang et al.(58) (Table 3.3).

The equation of the young's modulus:

$$E = \frac{\sigma}{\varepsilon} \tag{1}$$

E = Young's modulus, σ = stress, ε = strain

The equation of the Poisson's ratio:

$$\upsilon = \frac{\varepsilon_2}{\varepsilon_1} \tag{2}$$

υ = Poisson's ratio, ε_1 = longitudinal strain,

ε_2 = Transverse strain

The equation of the Ogden models:

$$W = \sum_{i=1}^{N} \frac{2\mu_i}{a_i^2}\left(\bar{\lambda}_1^{a_i} + \bar{\lambda}_2^{a_i} + \bar{\lambda}_3^{a_i} - 3\right) + \sum_{i=1}^{N} \frac{1}{D_i}(J-1)^{2i} \tag{3}$$

W is strain energy function. λ_1, λ_2 and λ_3 are the principle stretches. J is elastic volume ratio. μ_i is related to the initial shear modulus of the material. a_i and D_i are the parameters of material.

Table 3.2 Material properties of tooth, cortical and cancellous bone and stainless steel.[59]

Material	Young's modulus (MPa)	Poisson's ratio
Dentin	19613.3	0.15
Cortical bone	13700	0.26
Cancellous bone	1370	0.3
Stainless steel	200000	0.3

Table 3.3 Material properties of the PDL. The coefficients of the third order Ogden models.[58]

i	μ_i	α_i	D_i
1	-24.4237016	1.99994222	4.87164332
2	15.8966494	3.99994113	0.00000000
3	8.56953079	-2.00005453	0.00000000

6. Definition of loading condition

To simulate the six maxillary anterior teeth intrusion, intrusive force was applied to the arch wire.

In anchorage design 1 (one-mini-screw design), the net force of 60 g was applied to the middle of the arch wire between the central incisors. The force was divided to the y, and -z -axis with the 80-degree angle from the occlusal plane. This angle was calculated from the commercial maxillary model. (Figure 3.7)

In anchorage design 2 (two-mini-screw design), the net force of 60 g was applied to the arch wire between the lateral incisor and canine. The net force was divided by two to be the force magnitude for left and right side. The force of each side was divided to the x, y, and -z -axis in the left side and x, y and z -axis in the right side. This angle was calculated from the commercial maxillary model and shown in the figure 3.8.

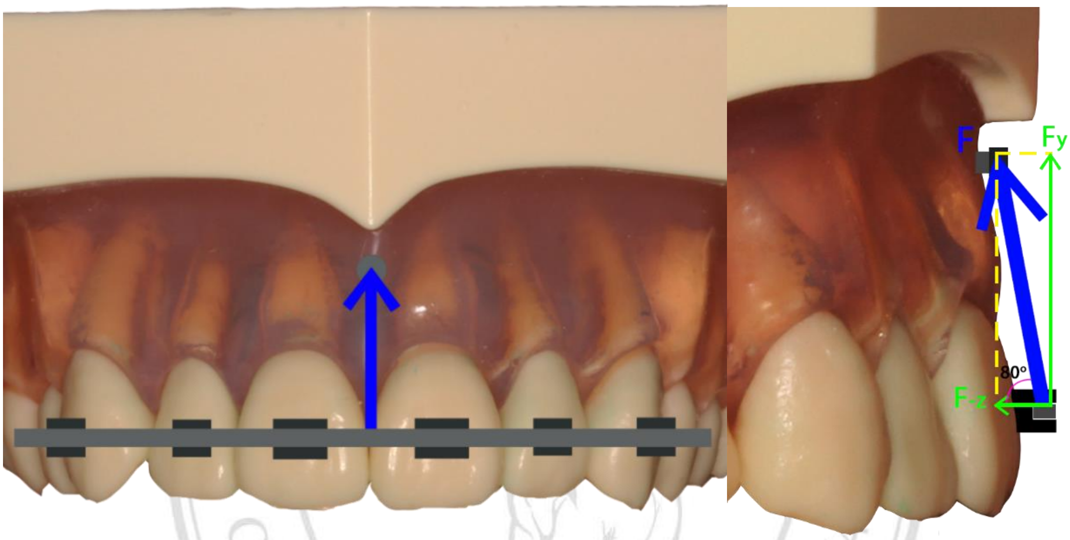
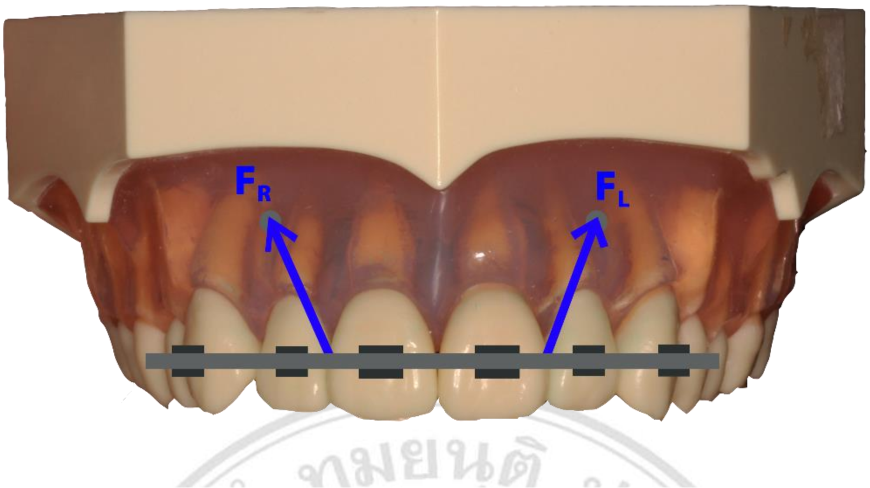
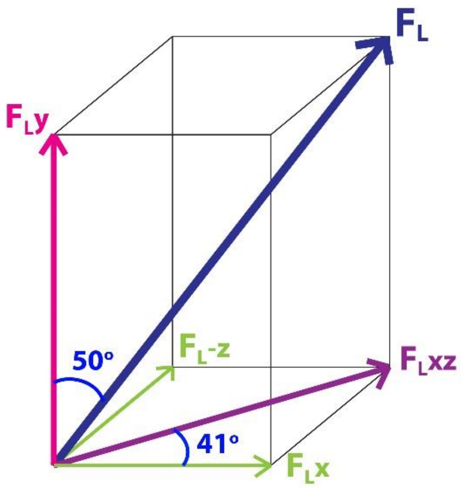


Figure 3.7 The force in anchorage design 1 was applied to the arch wire between the central incisors. The force was oblique along the contour of the teeth and gum about 80^{o} to the occlusal plane. The force was divided to the y and -z -axis and input to the Abaqus program.





$$F_{net} = F_R + F_L$$

$$F_L = F_Lx + F_Ly + F_L\text{-}z$$

$$F_Lx = F_L\sin50\cos41$$

$$F_Ly = F_L\cos50$$

$$F_L\text{-}z = F_L\sin50\sin41$$

Figure 3.8 The forces in anchorage design 2 were applied to the arch wire between the lateral and central incisor, left and right. A) The net force was divided by 2 to be the right force (F_R) and left force (F_L). B) The picture shows the division of F_L by the angle calculated from the commercial maxillary model. F_R was equal to the F_L, but F_R-x was opposite direction to the F_Lx.

3.3.4. Data results and analysis

1. The distribution of von Mises stress in the PDL

After applications of force, the von Mises stress in PDL was evaluated. Patterns of stress distribution were described from the numerical output and the color of graphic output. The unit of the stress was Mega Pascal (MPa) or N/mm^2. The color-coded map showed the great stress in red-colored area and the less stress in blue-colored area.

2. The displacement of the teeth

The direction of the displacement represented with the direction of an arrow, and the distance of the displacement represented with the length and color of the arrow. The unit of the distance was millimeter (mm). The comparison of before and after-load showed in with the superimposition of each teeth.