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Effect of Preparation Design for All Ceramic Restoration on Anterior Teeth- A 3d Finite Element Study – An Invitro Study

[1]Dr. M. Ramakrishna, PG Student of Sree Sai Dental College and Research Institute

[2]Dr. Sudheer.A, M.D.S, HOD of Department of Prosthodontic, Sree Sai Dental College and Research Institute

[3]Dr.Y. Ramesh Babu, M.D.S, Practitioner

[4]Dr. L.Srikanth, M.D.S, Sr. Lecturer, Sree Sai Dental College and Research Institute

[5]Dr.Lalitha Srivalli, M.D.S, Asst Prof, National Institute for Mentally Handicapped

[6]Dr.Sowmya Sree, Pg Student, Sree Sai Dental College and Research Institute

Corresponding Author: Dr. M. Ramakrishna, Pg Student of Sree Sai Dental College and Research Institute

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Abstract

Purpose: The study aims to investigate and quantify the effect of convergence angle in anterior tooth prepared with standard preparation height and restored with two different CAD/CAM ceramic crowns by three-dimensional finite element analysis.

Method: In the present study, a human maxillary anterior tooth restored with an all-ceramic crown was selected for the numerical analysis to find out maximal principal stress. A restored human maxillary anterior teeth was digitized by a MEDIT Tseries scanner and a 3D model was created by a meshlab software . Following segmentation, dentine and ceramic were extracted by a surface meshing software (3-matic). Models with different preparation designs with three convergence angles (10^0, 20^0 and 30^0) and with standard preparation heights (7mm) were produced. Mesh generation for models was performed in IA-FEMesh software with a lithium disilicate glass ceramic (LD, E = 95.9 GPa) and a polymer-infiltrated ceramic (PIC, E = 30.1 GPa) as the restorative materials.. 18 models were analyzed numerically in Ansys 16.2.

Results: The results showed that Convergence was found to be a major factor affecting stress distribution. In all models, the maximum principal stress for all ceramic crowns was found in cervical area of the tooth and there is an increase in the magnitude of maximal principal stress when the convergence angle of tooth increased from 10 degrees to 30 degrees and also depended on the materials.

Conclusions: The convergence angle of the tooth and material used for restoration play an important role in stress distribution on the tooth.

Keywords: Finite Element Analysis (FEM)

Introduction

The prime objective of prosthetic rehabilitation is to improve and maintain the quality of life in the patients. It can be accomplished by preventing diseases, improving mastication, relieving pain, enhancing speech and improving aesthetics.[1] The development and selection of biocompatible materials for a prosthesis which can resist the specific conditions of the oral environment has been the main challenge since centuries.[2]

A full-coverage crown is a standard method for restoring damaged teeth due to caries, wear, and trauma.[3,4] An ideal restoration should provide a reliable long-term performance.[4,5] Because of the increasing aesthetic demand, All-Ceramic materials are widely used in dentistry because of their biocompatibility, chemical inertness, good compressive strength and abrasion resistance, low plaque accumulation, superior esthetics, and colour stability. However, their low tensile and flexural strength make the material brittle and sensitive to flaws and defects. The applied stresses resulting from masticatory loads concentrated on the inherent flaws that exist in the ceramic, which can amplify applied stress leading to rapid crack propagation that can, in turn, lead to brittle fracture of the ceramics. As a result, ceramic materials probably fracture at a fraction of their theoretical strength due to the flaws' stress-raising effect.[5,6] It has shown that porosities and microcracks are the sites of fracture initiation.

Apart from the material strength, tooth preparation, and restoration design also have appreciable effects on fracture resistance of all-ceramic crowns.[7,8] Various designs for full-coverage restorations, including margin thickness,[9,10] preparation height, and margin adaptation,[11,12] have been studied. While convergence angle is one of the determining factors affecting the stress distribution and thereby survival of a restoration,

The drawbacks of traditional porcelains like voids and imperfections produced during fabrication procedure are known to be the weakest link in ceramic crowns.[13] To overcome the problem, new materials and technologies such as CAD/CAM ceramics, have been developed.[14,15] CAD/CAM ceramics are more homogeneous in structure, and they could mill into a full restoration with minimal processing.[16] Furthermore, CAD/CAM technology has facilitated the scanning of complex tooth geometry which used for ceramic manufacturing.[17] CAD/CAM restorations have accurate marginal adaptation, and they could fabricate at chairside, and that saves time and minimises laboratory cost.[13]

When specimens that resemble the shape of crowns and fixed partial dentures (FPDs) used, mechanical behaviour may be closer to the clinical situation. However, the evaluation of the stress distribution within complex geometries is limited.[18,19] This situation can overcome using finite element analysis (FEA), which is a fast and relatively low-cost method. Used to investigate stress distribution and strain patterns of complex structures, such as dental restorations FEA can be used for: (1) to understand the failure behaviour of complex structures, or (2) to optimise the experiments through the mathematical simulation and selection of the best design to perform the test.[20] The necessary steps involved in this method are pre-processing, solving and post-processing. The objective of current study is to investigate the effect of convergence angle with standard preparation height on the stress distribution of a restored maxillary anteriors with two CAD/CAM ALL Ceramic crowns using FEA.

Materials

The Von Mises stresses on axial loading on the different convergence angles of tooth preparation on anterior maxillary teeth was calculated using the three-dimensional finite element analysis that created on a computer with the following configurations:

Hardware

CPU unit: An Intel Pentium 4 or Xeon-based workstation Windows XP

Memory: 512 MB of RAM

Disk drive: 8 G.B. Disk Drive space

Display: Compatible graphic colour display

Graphics adapter: A graphics adapter with a 3D OpenGL accelerator with a minimum resolution of 1024x768 pixels for Microsoft Windows workstation.

Software

MeshLab2016.12.exe

CATIA V5(application), ANSYS version 16.2

Methodology

In the present study, a human maxillary anterior tooth restored with an all-ceramic crown was selected for the numerical analysis to find out maximal principal stress. Two parameters, including three convergence angles (10^o, 20^o and 30^o) and standard preparation height (7mm) investigated.

Additionally, two CAD/CAM ceramics considered as the restorative materials for the crown, a lithium disilicate glass-ceramic (L.D., IPS e.max CAD, Ivoclar Vivadent, Schaan, Liechtenstein) and a polymer-infiltrated ceramic (PIC, Enamic, VITA Zahnfabrik, Bad Säckingen, Germany). RelyXTM Ultimate (3M ESPE, St. Paul, MN, USA) utilised as the adhesive resin cement layer.

Application Of Finite Element Analysis

A three-dimensional finite element solid model of the human maxillary anterior teeth was constructed based on C.T. data. The TIFF-format images taken from the MEDIT Tseries scanner were reconstruct using colLAB 2017 software (MEDIT) for reaching the final bitmap (BMP) files.e).In order to construct a more precise model, the slices edited manually by Meshlab2016.12.

After constructing the model, the adhesive mask was created by applying the Boolean operation function, which could reduce the working time with accurate boundaries between the masks. After completion of the 2D masks, their 3D shapes generated and the stereolithography (STL) file of each mask extracted.

The STL files were imported directly to a 3-Matic workplace where advanced manipulation of the volumetric files and design could perform. The smoothing operation used to remove inappropriate and sharp triangles that covered the surfaces of dentin and ceramic (fig-1) Tessellated surfaces of dentin and ceramic extracted in Initial Graphics Exchange Specification (IGES) file format(fig-2)The IGES files imported to CATIA V5 software in order to frame the models with desired dimensions taken from wheelers 9th edition.

As the imported files were in a format of surface, they (dentin and ceramic) were converted to a definite format using the Knit surface tool. By applying extrusion and cutting functions on different surfaces of dentin, standard abutment height and different convergence angles created. Combining function was used, so the intaglio surface of ceramic could fit on the modified dentin with the incisal surface of ceramic remained unchanged.

To mimic the clinical situation, a layer of adhesive with a thickness of 100 microns between the dentin and ceramic.

Dentin, ceramic, and adhesive STL files extracted. The resultant 3D models obtained according to their convergence angle and preparation height (Fig. 3-11):

CIT10H — 10^o convergence angle and 7mm height preparation

CIT20H — 20^o convergence angle and 7 mm height preparation

CIT30H — 30° convergence angle and 7mm height preparation

LIT10H — 10° convergence angle and 7mm height preparation

LIT20H — 20° convergence angle and 7 mm height preparation

LIT30H — 30°convergence angle and 7mm height preparation

CT10H — 10° convergence angle and 7mm height preparation

CT20H — 20° convergence angle and 7 mm height preparation

CT30H — 30° convergence angle and 7mm height preparation

Afterwards, by assigning the two restorative materials (L.D. and PIC) as the crown, 18 models were created.

To generate the desired mesh for each part, the IA-FEMesh software used for a high-quality mesh. By importing the IGES files to generate nodes, hexahedral elements generated for each part. All of the connections between the elements considered as bonded. The mechanical properties boundary conditions and the nature of loading obtained from the literature. The boundary conditions determined as fixed support. The models were assumed to be homogenous, isotropic, and linear elastic. The Young's modulus and Poisson's ratio flexural strength values entered into ANSYS 16.2 software which automatically calculated the maximal principal stress of convergence angle(10°,20°,30°) of anterior maxillary teeth restored with L.D., PIC CAD/CAM crowns.

Table 1: Properties of Members

Material	Young’s modulus (MPa)	Poisson’s ratio	Compressive strength (MPa)	Flexural strength (MPa)
LD ceramic	95,900	0.23	To be evaluated	356.7
PIC ceramic	30,100	0.23	To be evaluated	135.8
Enamel	84,100	0.33	95-386	30-35
Dentine	18,600	0.31	249-315	40-276
Adhesive cement	7700	0.3	262	98

Table 2: Nodes and Elements

Model	Nodes	Elements
Central Incisor	24105	14042
Lateral Incisor	18210	10637
Canine	13150	7543

Discussion

FEA considered being an excellent alternative to explore the behaviour of all-ceramic crowns. In the present study, the effect of the convergence angle on the stress pattern of maxillary anterior (FEM) investigated central incisor, lateral incisor, canine restored by an all-ceramic crown.

FEA represents a powerful tool to understand the mechanical behaviour of all-ceramic crowns and to optimise the design of future tests.[20] However, the analysis may be limited by difficulties related to model generation.[23] To overcome this problem, the present study described a modelling technique, combining scanned images and interactive image control software, which resulted in valid 3D FEA models. C.T. scanner was developed in the 1980s for laboratory purposes on small samples and material experiments and emerged as a potential essential tool in dental research.

Many advantages are related to this technology:

(1) The relative ease of using equipment and software;

(2) Fast and non-destructive method.[20]

(3) High resolution.

(4) 3D reconstruction of complex structures (i.e. bone, root canal, dental restorations).

(5) Quantitative and visual measurements for biomaterials.[21,24]

The Individual parameters related to the scanning process (i.e. exposure time, filter, and rotation) and to the image reconstruction (i.e. beam hardening and ring artefact) can influence dimensional results and produce significant errors.[28]

Although some systems are capable of reading C.T. data and converting them to a finite element model, many programs have limited tools to select and edit the parts of interest.

The Meshlab software used as an interface between the C.T. scanning and the FEA software (ANSYS) to fulfill the requirements for creating accurate and highly detailed F.E. models.[22]

A considerable effort performed using a set of software to achieve an accurate F.E. model. The models contained ceramic crown, dentin, adhesive, enamel while most studies did not take the remained enamel into account. This simulation was robust because three-dimensional hexahedral elements were used, which could produce more accurate results compared to the conventional approach using tetrahedral elements.

The models investigated are in the same range and validation of 18 models with experimental results regarding the current study. It observed that the tooth with less degree of convergence angle, i.e. 10^{O} degrees in both materials L.D. & PIC showed low MPS values of ceramic.

The static load analysis performed in this study is an acceptable method to assess the mechanical behaviour of tooth.[10] However; it should note that cyclic fatigue leads to failure of dental restorations in clinical conditions which usually happen in subcritical loads.

Homaei et al. expressed a fatigue limit which was approximately half of the mean static flexural strength, below which no failure expected to occur.[57]

According to this limit and flexural strengths of two ceramic crowns (Table 1), MPS of PIC ceramic was more close to its half of flexural strength in comparison with L.D. However, the resistance of PIC against crack propagation is increased considerably in cyclic loadings, in particular when used as a crown.

L.D. Glass-ceramic is known as a brittle material, whereas the plastic behaviour of PIC postpones fatigue failure.[30] Therefore, both materials seem to be reliable under cyclic masticatory forces as a crown restoration for maxillary anteriors.

An essential factor of the fracture resistance is the margin thickness. Increasing the margin thickness could allow the restoration to withstand a more significant axial load before it fractured However, it has a limit, and it recommended that the margin thickness for all-ceramic crowns should range from 0.5 to 1.0 mm[11] and that has adopted in the present simulated model.

In the present study, the 10^{O}-degree design found to be the best convergence angle for both ceramic materials with lower stresses compared to other angles. Variations in the convergence angle displayed the difference in stress values in the ceramic crowns.

In models with standard height, the MPS of dentin in the 10^0-degree group was lower than the group with 20^o and 30^o degrees of the same tooth. It might be due to the more surface area to distribute force which resulted in more excellent retention.

The MPS of enamel component in the L.D. group was greater than that in the PIC group. Since L.D. Ceramic has a greater elastic modulus, higher stresses created and that could transfer to the enamel at the margin which considers being a supporter of the crown.[27]

It might be related to the fact that a stiffer crown-like L.D. Caused greater stresses values to be generated in enamel. Indeed, the considerable difference between the flexural strengths of L.D. Crown (356.7 MPa) and enamel (30–35 MPa) might lead to a more unbalanced stress distribution between both the L.D. Crown and enamel where a more robust material (L.D. crown) placed on a weaker material(the remained enamel at the margin of the restoration).

Additionally, a steeper preparation design (greater convergence angle) resulted in greater Tresca stress values stated in the literature.

In a realistic situation of tooth-to-tooth or food bolus-to-tooth contact, non-linear analysis considers being a promising method to evaluate the stress and strain state within the tooth structure.[21]

In this study, the load applied at the incisal surface of the tooth more palatally which mimic the natural biting force of the tooth. Because concentrated forces often impose excessive stress around the loading point, which is far from the real condition of tooth-to-tooth contact.[27]

Besides, increasing MPS values in the ceramic at the cervical area of the tooth model increases the ceramic's vulnerability to radial cracks developing. Furthermore, in the models with more massive abutment and indeed thinner ceramic thickness, the appropriate ceramic material is expected to withstand more tensile stress (here L.D.) but maximal principal stress we can notice at the cervical one-third of the tooth surface which leads to half moon fracture.[27]

Since the oral cavity is a complex biological system with limited access, most of the research work regarding oral environment like in restorative dentistry, orthodontics, implantology, prosthodontics, is being conducted in vitro.

FEA is nothing but a mathematical way to resolve complex problems in the universe.

In each element, it entails a series of computational procedures to compute the stress and strain. FEA effectively sculpts the tooth and periodontal structures by isolating the problem domain into a group of much smaller and simpler domains.

A discretisation of the structure done into "elements" that connected through nodes

Several engineering software is present for the modelling and simulation of different structures of interest.

In the past years, basic assumptions were made for simulating geometry, boundaries and also for load and material properties which ultimately affected the analysis.

There are many variations in the human body regarding bone quality, quantity, shape, which further impacts the prognosis of dental treatment. So, with the advancement of digital image systems, extrapolation of individual definite data of bone geometry to a model has become possible. A computerized tomography, C.T. scans the image of the tooth and bone three-dimensional level, which leads to the creation of accurate anatomical models that provide consistent results.[29]

Thresher and Farah did the usage of FEA in oral research in 1973. In 1976, Weinstein utilized this in implant dentistry.[29]

Available commercial FEM software.[30,31]

ANSYS (General purpose, P.C. and workstations)

SDRC/I-DEAS (Complete CAD/CAM/CAE package)

NASTRAN (General purpose FEA on mainframes)

LS-DYNA 3D (Crash/impact simulations)

ABAQUS (Non-linear dynamic analysis)

NISA (A General-purpose FEA tool)

PATRAN (Pre/Postprocessor)

HYPERMESH (Pre/postprocessor)

Steps in FEA: [31]

1. Discretisation of problem.
2. Imaging.
3. Meshing.
4. Boundary conditions.
5. Types of solutions.

Parameters which define the accuracy: [31]

1. Geometry
2. Material properties
3. Loading conditions
4. Boundary conditions

Applications:[31]

Useful in ascertaining stress distributions within teeth, in the cavity preparation design and also in restorations.

To evaluate the biomechanical tooth movement.

The periodontal ligament can examine when forces applied in orthodontic patients.

To assess stress distribution on teeth and associated structures in case of removable and fixed prosthesis designs.

It Allows in understanding the various implant designs regarding bone modelling, for evaluating the biomechanical behaviour of dental implants.

Useful in maxillofacial traumas, mandibular fractures, orthognathic surgeries, Viscoelastic and plastic behaviours in materials

Non-linear simulation of periodontal ligament property.

Advantages of FEA include, they apply to non-linear, linear, solid and fluid-structural interactions and is a non-invasive technique, results in easy simulation of any biological condition. Its reproducibility will not affect the dynamic physical properties.

It is less time-consuming, easily repeatable; no extensive instrumentation is required and can replace stereolithographic models, thus providing an economical solution for the same.[57,60]

Structural Static Analysis

Static analysis is one in which the loads/boundary conditions are not the functions of time and assumption here is that the load is applied gradually.

The most common application of FEA is the solution to stress-related design problems.

Typically in static a static analysis, the kind of matrix solve is

[K] X [X] = F

After obtaining the results, the values subjected to finite element approach, and the bar graphs plotted between different convergence angles(10^O,20^O,30^O) of the maxillary central incisor, lateral incisor, canine, with two different CAD/CAM crowns (L.D&PIC) on the x-axis, and the amount of maximal principal stress on the y-axis and the bar graphs obtained in Microsoft Excel.

According to the study, the Mpa values for 10^O-degree convergence angle restored with CAD/CAM L.D crowns produce values of CIT10H-22.191, LIT10H-23.221, and CT10H-22.912 and restored with CAD/CAM PIC crowns produce values of CIT10H-21.105, LIT10H-22.625, and CT10H-22.111.

The Mpa values for 20^O-degree convergence angle restored with CAD/CAM L.D crowns produce values of CIT20H-22.785, LIT20H-23.900, CT20H-23.250 and crowns restored with CAD/CAM PIC shows values of CIT20H-22.191, LIT20H-23.365, and CT20H-23.105.

The Mpa values for 30^{O}-degree convergence angle restored with CAD/CAM L.D crowns produce values of CIT30H-23.225, LIT30H-24.122, CT-23.915 and crowns restored with CAD/CAM PIC shows values of CIT30H-22.913, LIT30H-23.621, and CT30H-23.161.

The higher values of maximal principal stress recorded with LIT30H restored with Ivoclar IPS e.max (L.D.) was about 24.122 Mpa, and the lower values of maximal principal stress evaluated with CIT10H restored with VITA.Enamic (PIC) was about 21.105Mpa. It may be due to amount of reaming tooth structure to withhold the crown so the increase in convergence angle will reduce the proportion of tooth available for support of crown which leads to lack of retention and also depends on the material used for the crown. The rigid materials will cause more amount of stress when compared to brittle materials.

Conclusion

Finite element analysis has proven to be a precise and applicable method for evaluating stress on tooth. This method offers several advantages, including accurate representation of complex geometries, easy model modification and representation of the internal state of stress and other mechanical quantities. Hence it is routinely used in dentistry for determining stresses around the tooth.

The following conclusions are drawn from the study:

The tooth with 30^{O}-degree convergence angle restored with Ivoclar IPS e.max shows more amount of stress compared with teeth with 10^{O}-degree convergence angle restored with VIT.Enamic.

The convergence angle of the tooth and material used for restoration are factors for stress distribution on the too.

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Legend Figure

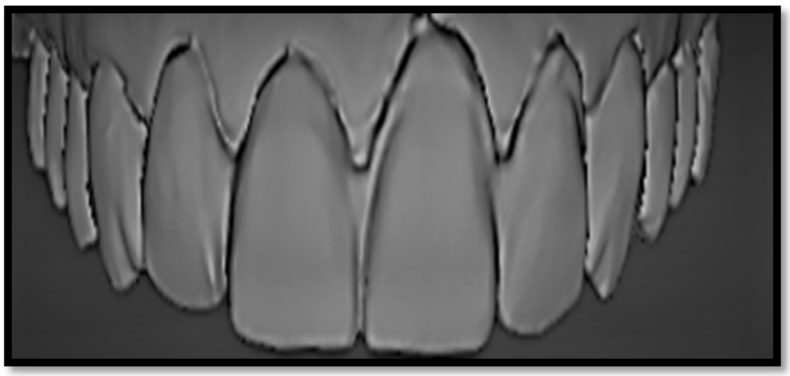


Fig 1: meshlab images with crowns in place

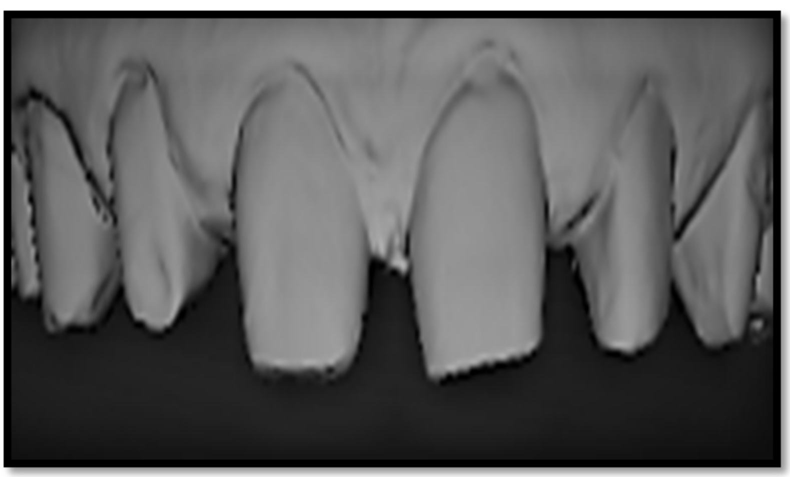


Fig 2: iges file format images separation of crowns

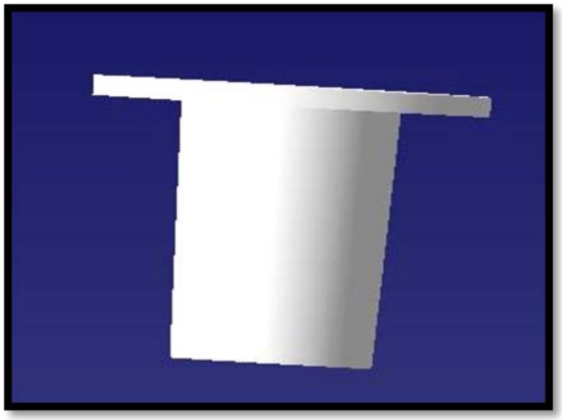


Fig 3: 10^{o} degree convergence of maxillary central incisor

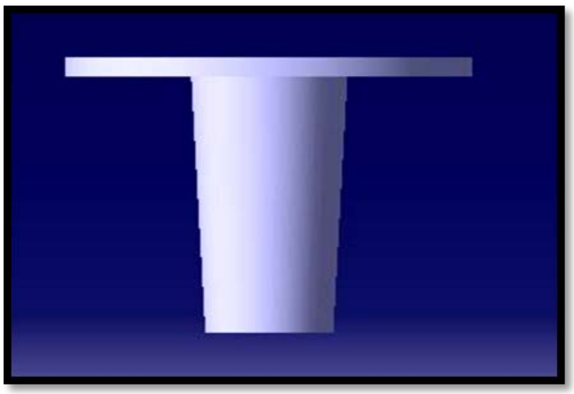


Fig 4: 10^{o} degree convergence of maxillary lateral incisor

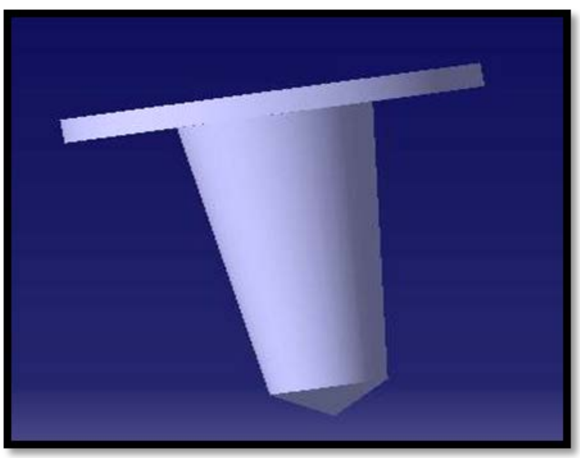


Fig 5: 10^{o} degree convergence of maxillary canine

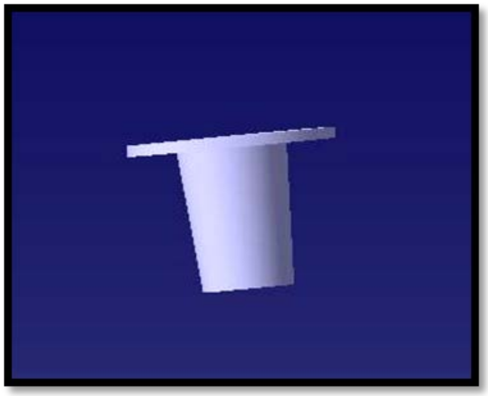


Fig 6: 20^{o} degree convergence of maxillary central incisor

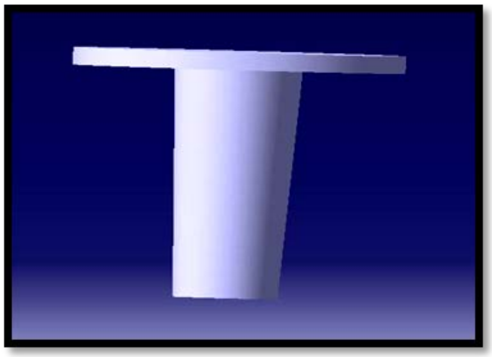


Fig 7: 20^{o} degree convergence of maxillary central incisor

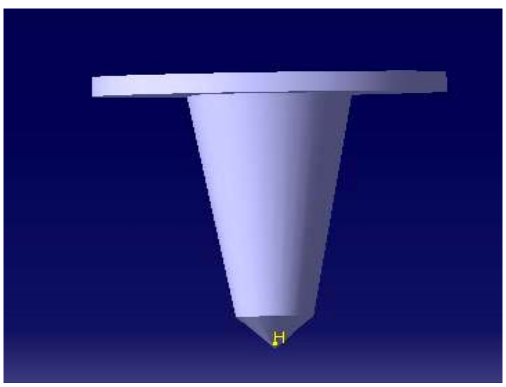


Fig 8: 20^{o} degree convergence of maxillary canine

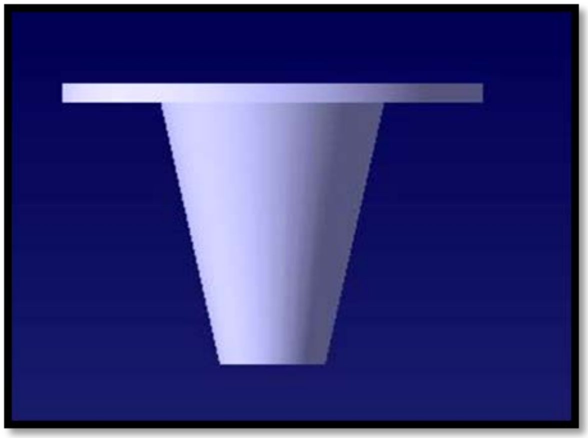


Fig 9: 30^{o} degree convergence of maxillary central incisor

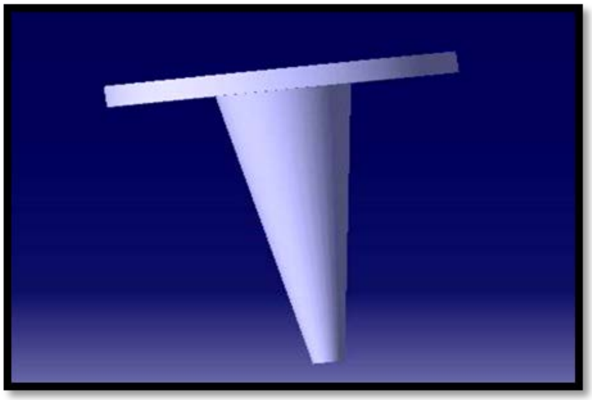


Fig 10: 30^{o} degree convergence of maxillary lateral incisor

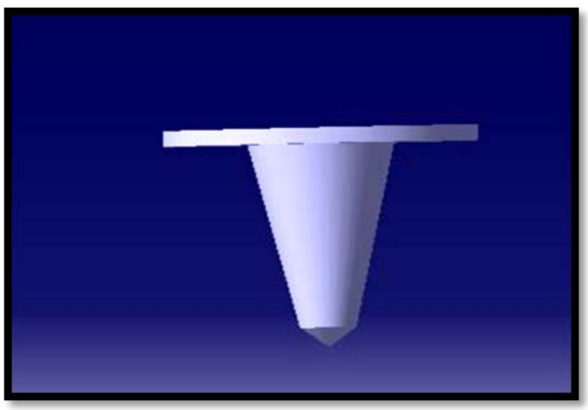


Fig 11: 30^{0} degree convergence of maxillary canine

Generation of mesh

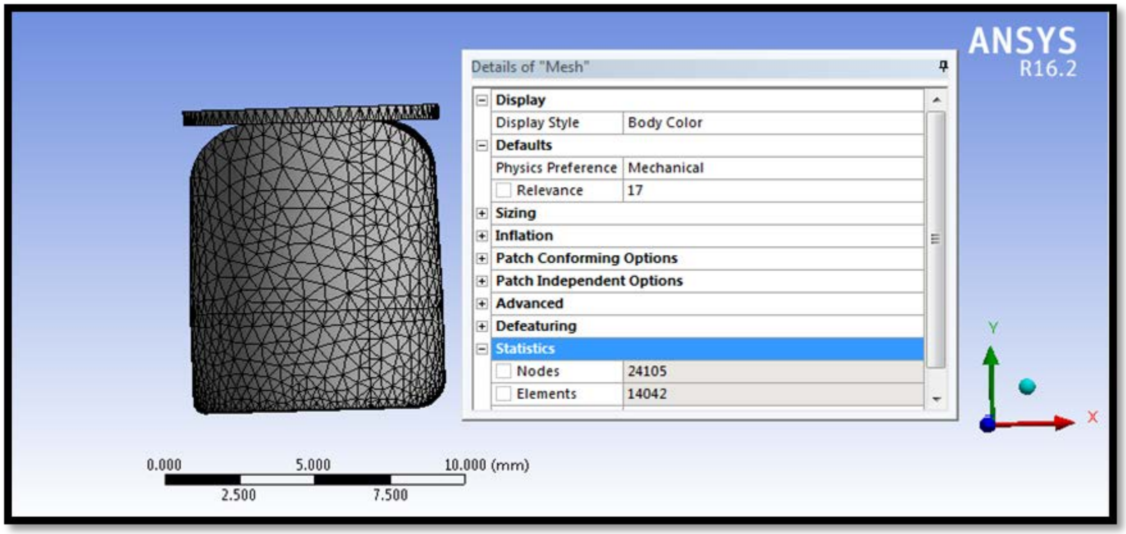


Fig 12: meshed maxillary central incisor

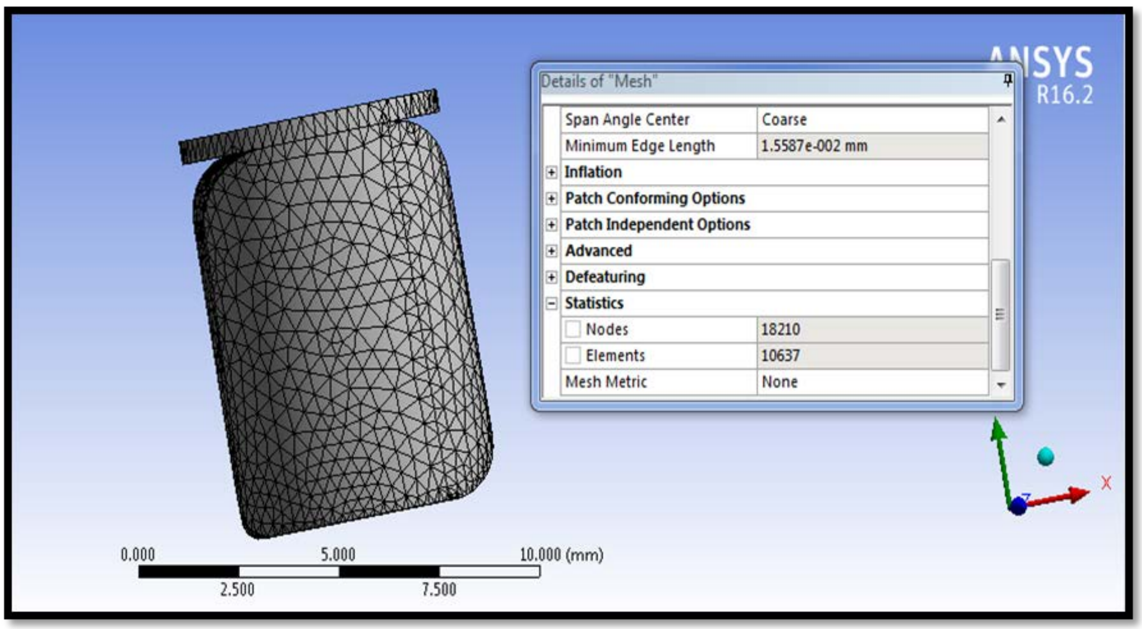


Fig 13: meshed maxillary lateral incisor

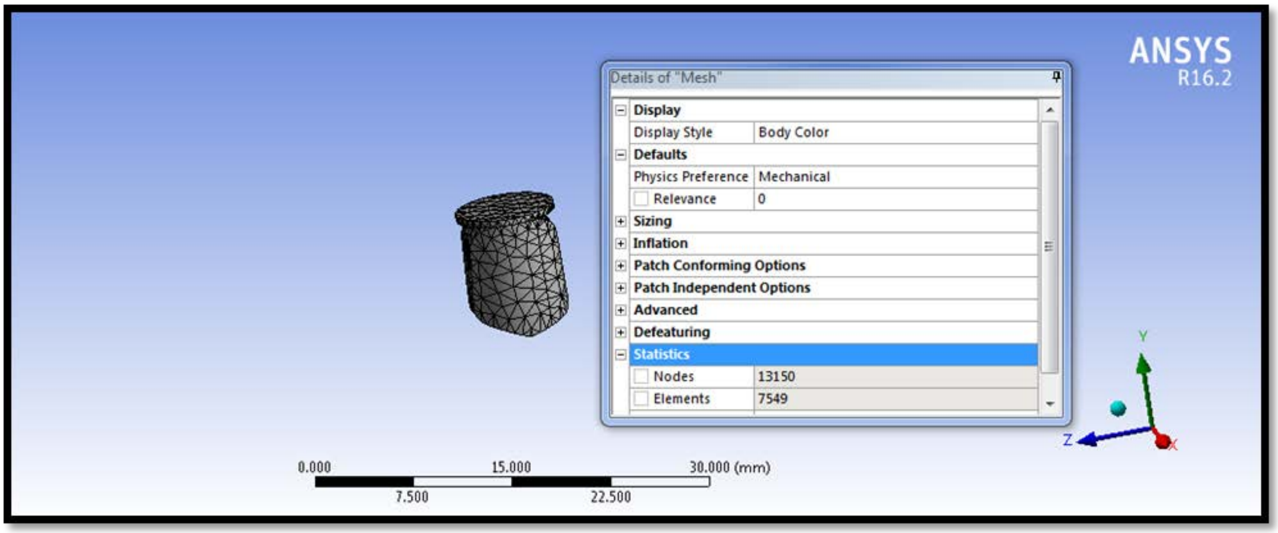


Fig 14: meshed maxillary canine

Boundary conditions

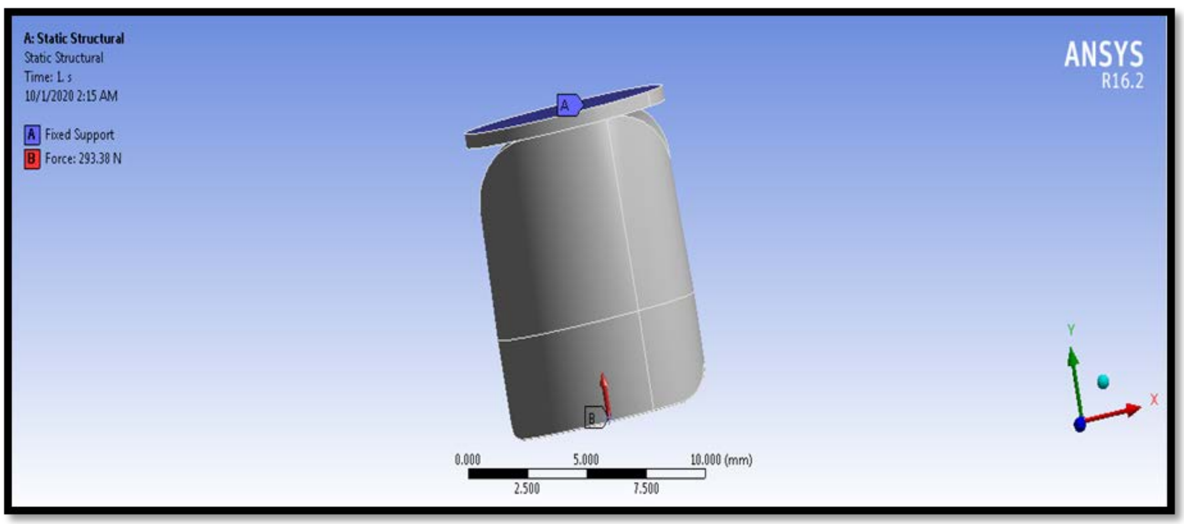


Fig 15: boundary conditions of maxillary central incisor

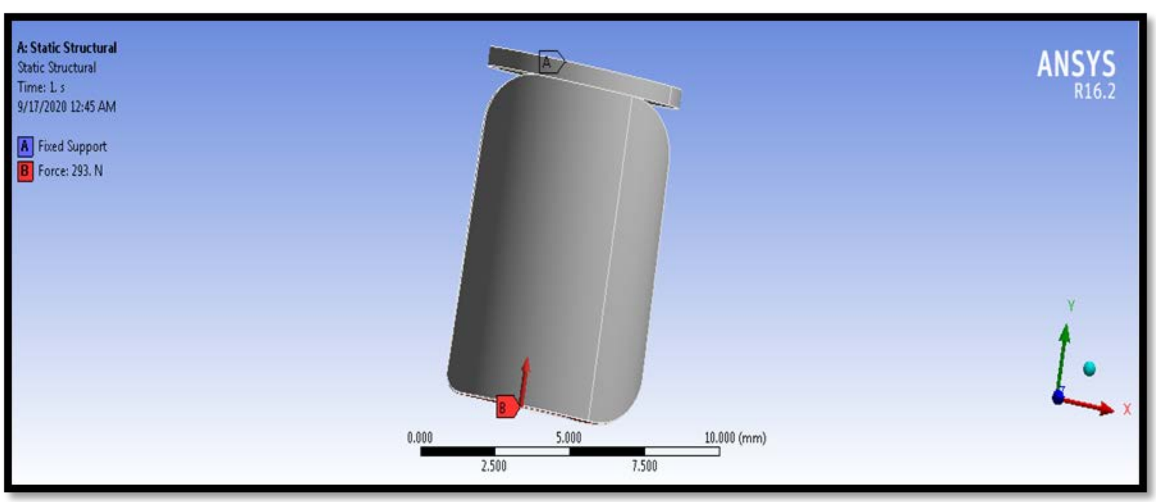


Fig 16: boundary conditions of maxillary lateral incisor

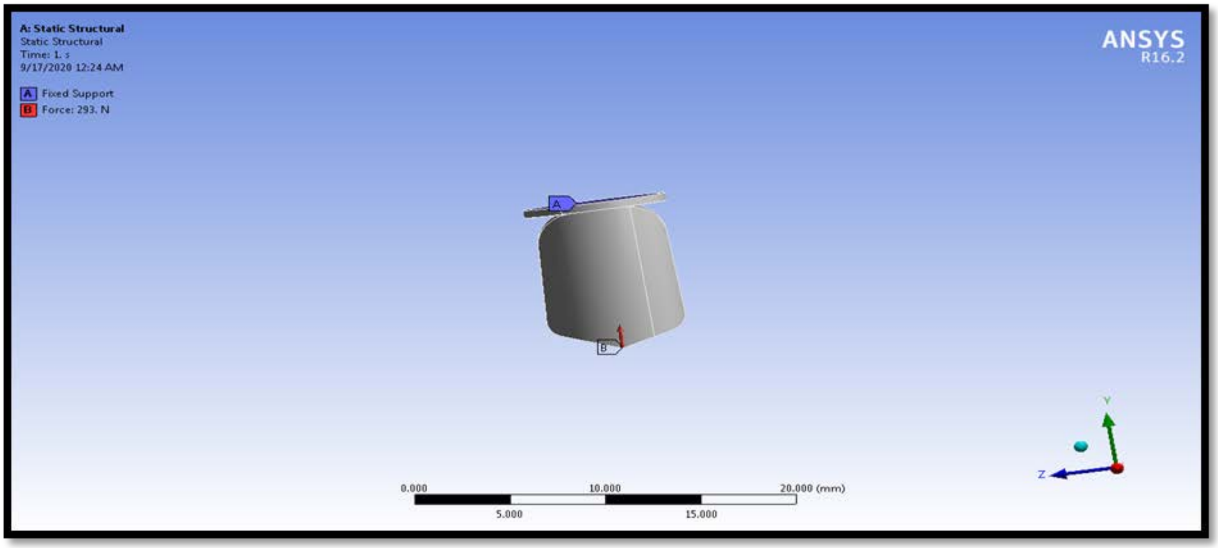


Fig 17: boundary conditions of maxillary canine

Maximal principal stress when load applied and restored with pic (vita enamic)

10^{o} degrees angle:

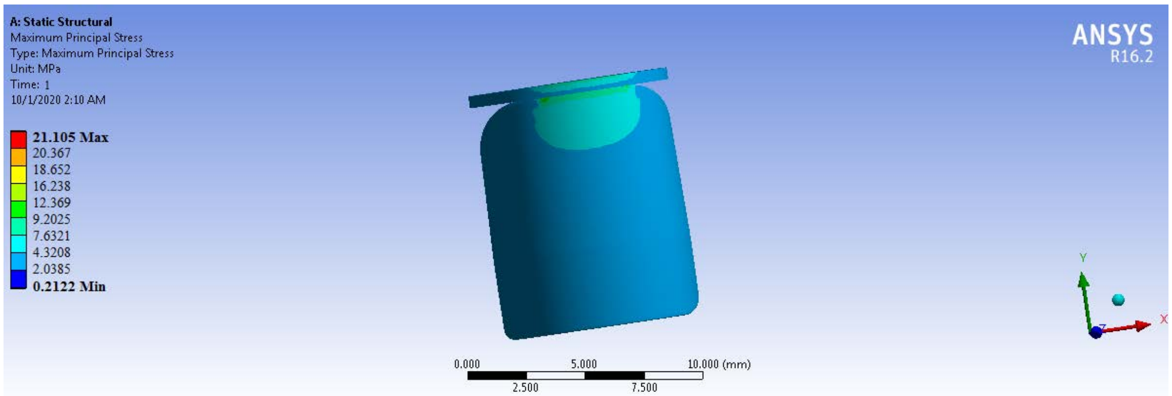


Fig 18: maxillary central incisor

Fig 19: maxillary lateral incisor

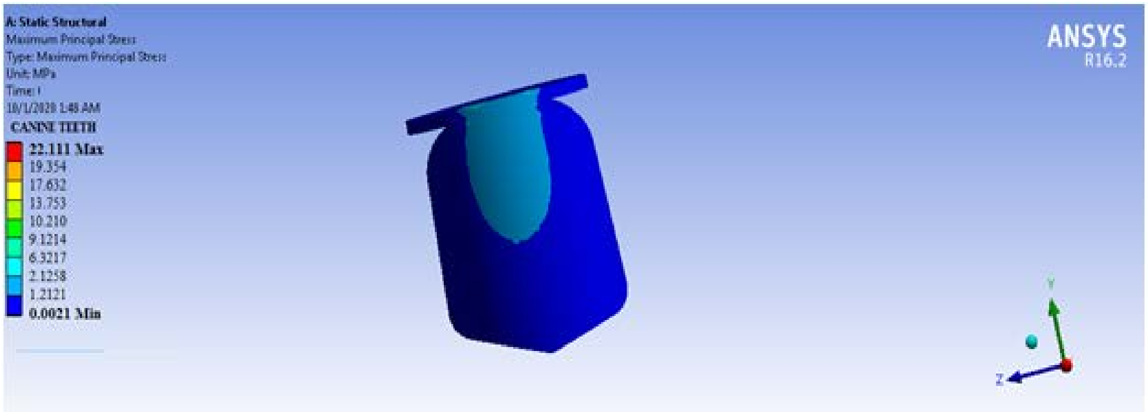


Fig 20: maxillary canine

20° degrees angle:

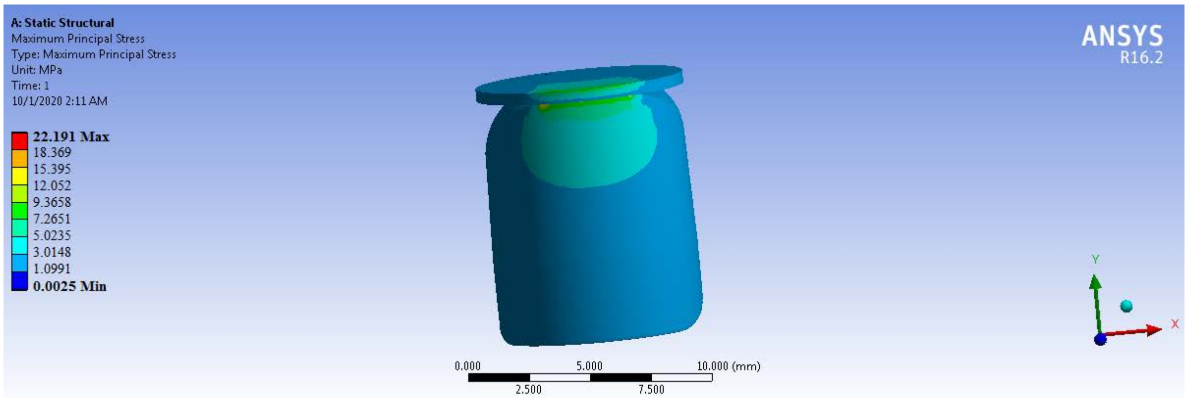


Fig 21: maxillary central incisor

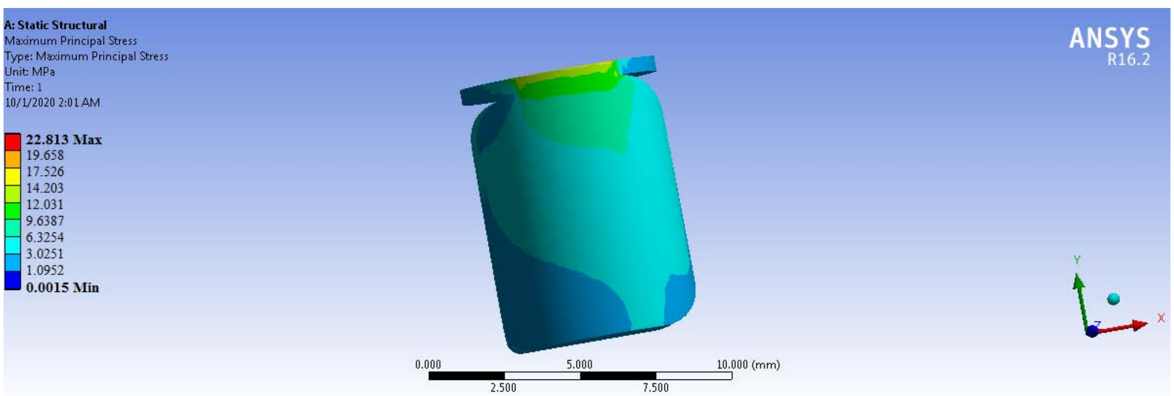


Fig 22: maxillary lateral incisor

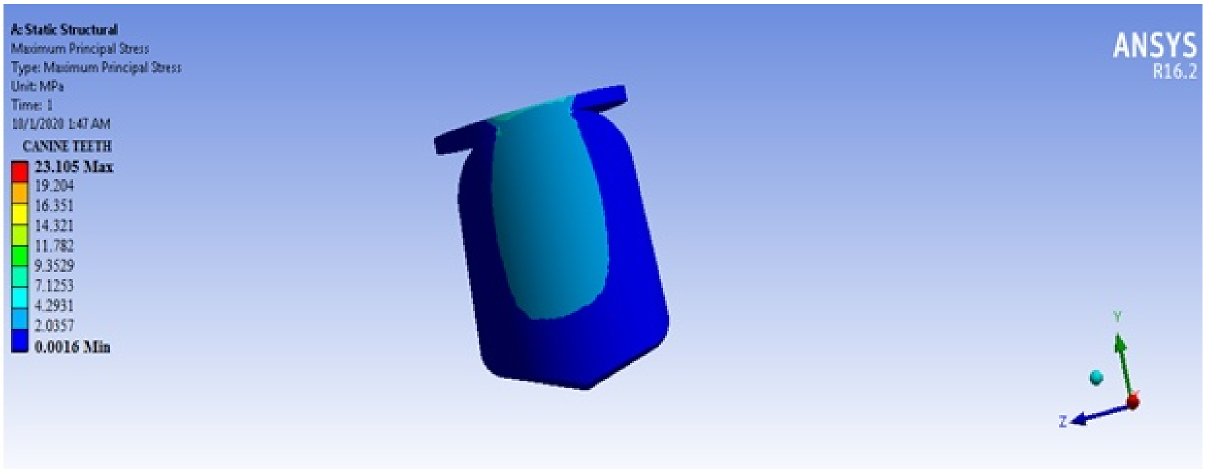


Fig 23: maxillary canine

30^0 degrees angle

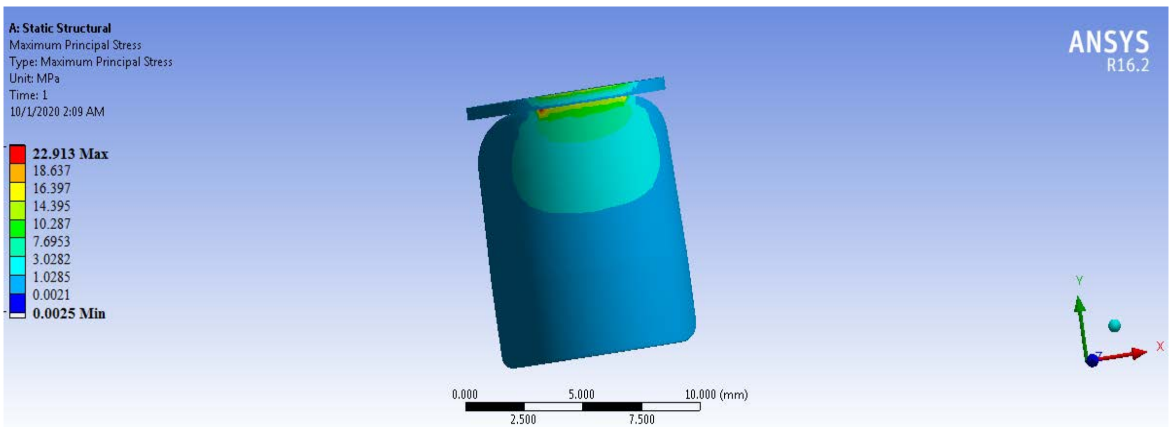


Fig 24: maxillary central incisor

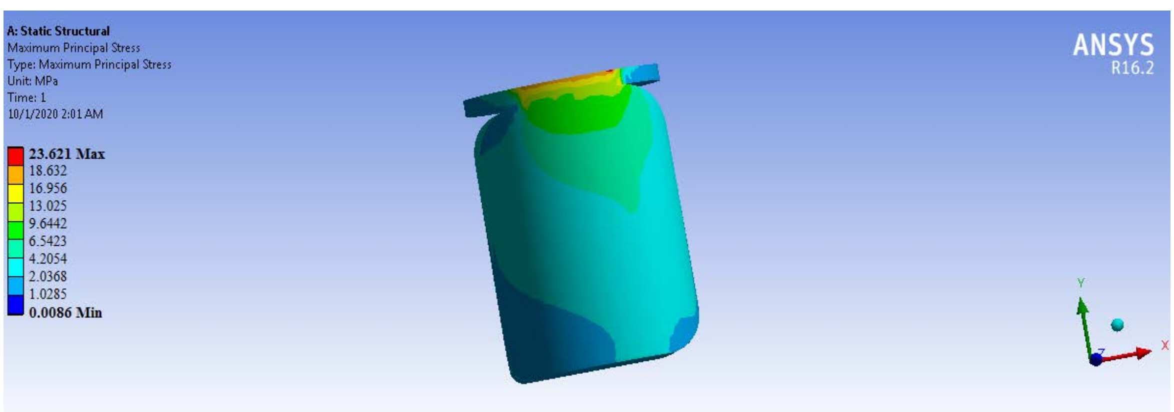


Fig 25:maxillary lateral incisor

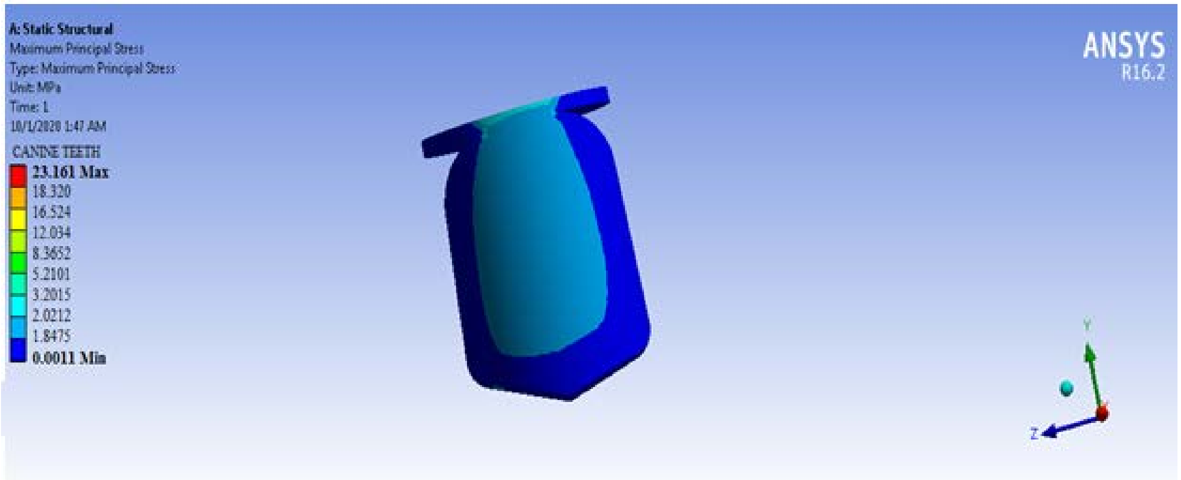


Fig 26: maxillary canine

Maximal principal stress when load applied and restored with ld (ips e.max)

10^{o} degrees angle

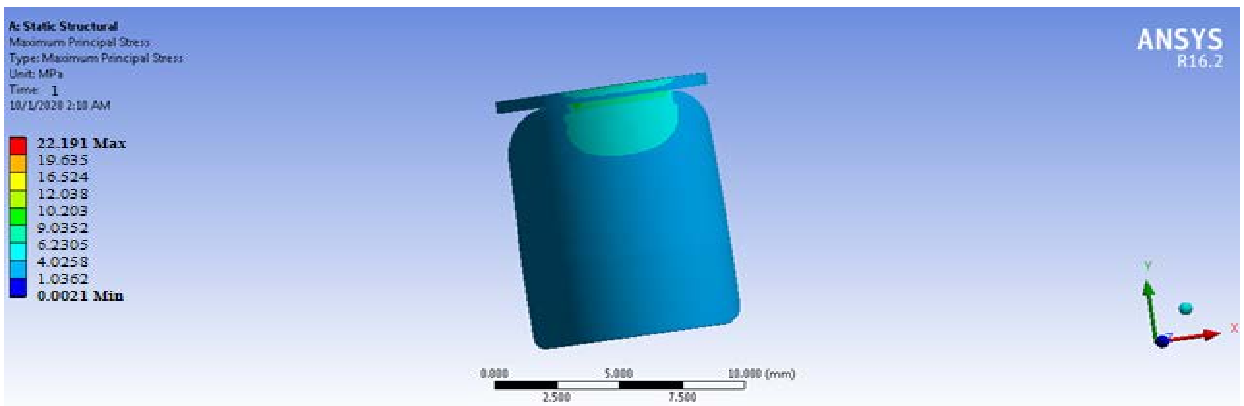


Fig 27: maxillary central incisor

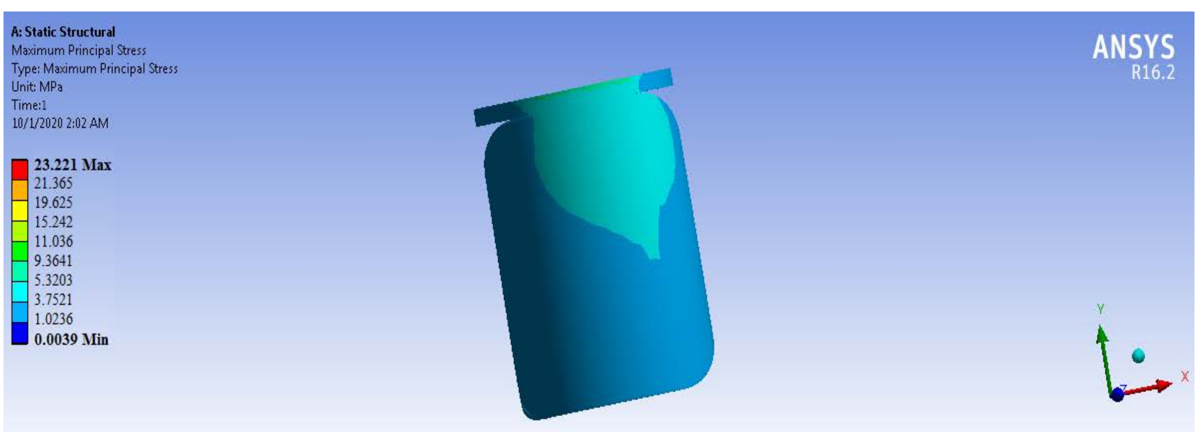


Fig 28: maxillary lateral incisor

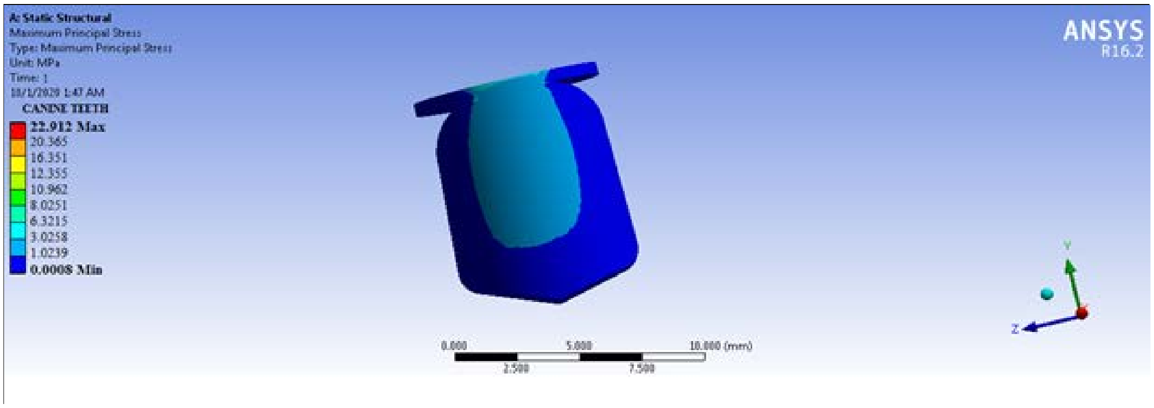


Fig 29: maxillary canine

20^o degrees angle

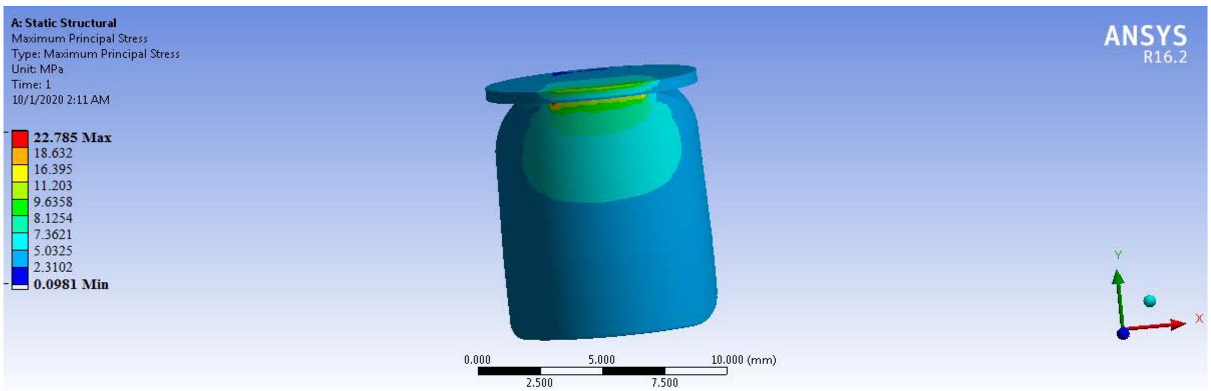


Fig 30: maxillary central incisor

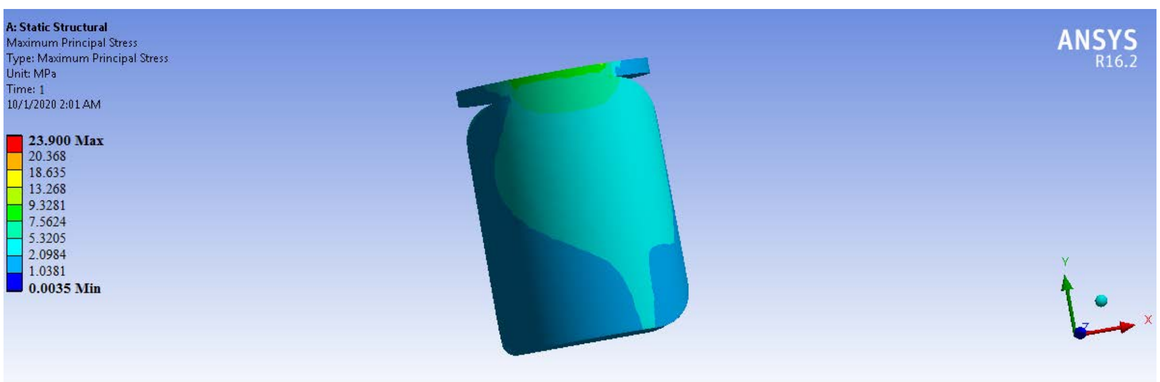


Fig 31: maxillary lateral incisor

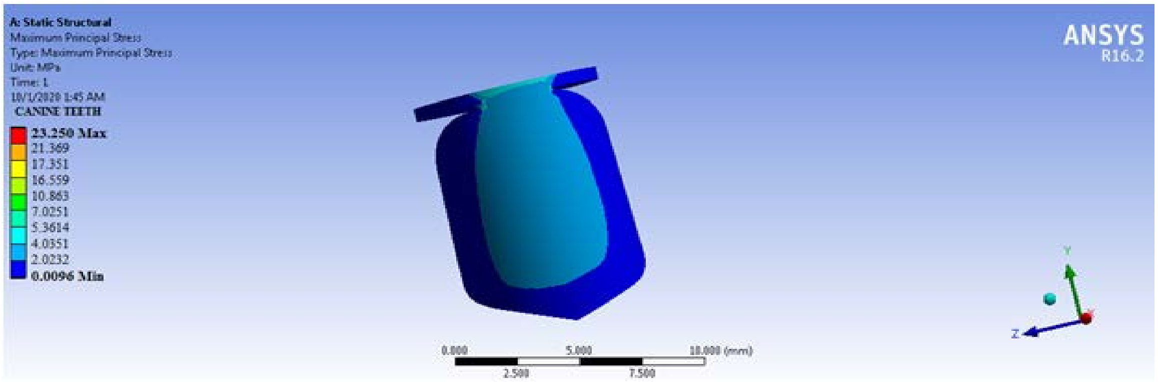


Fig 32: maxillary canine

30^{o} degrees angle:

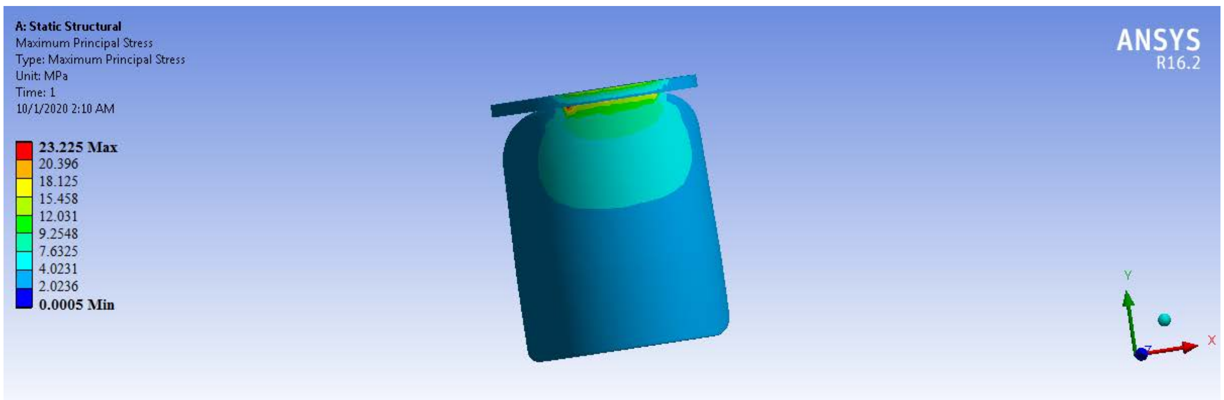


Fig 33: maxillary central incisor

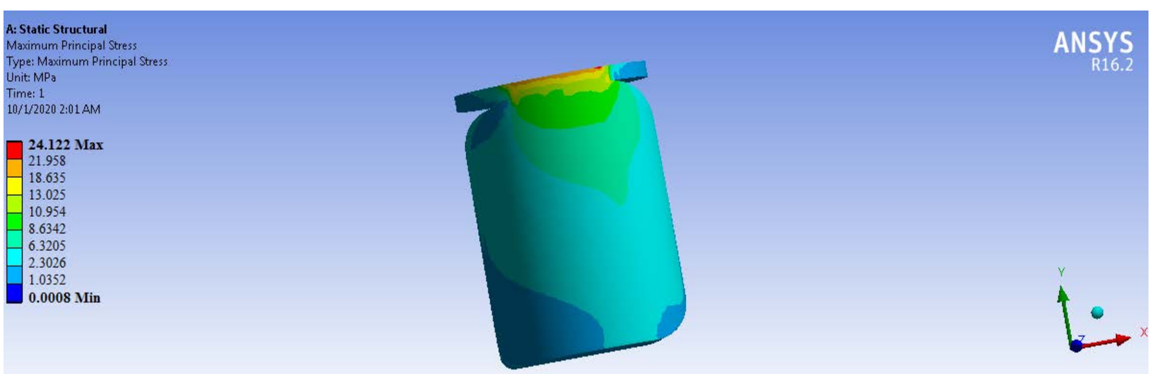


Fig 34: maxillary lateral incisor

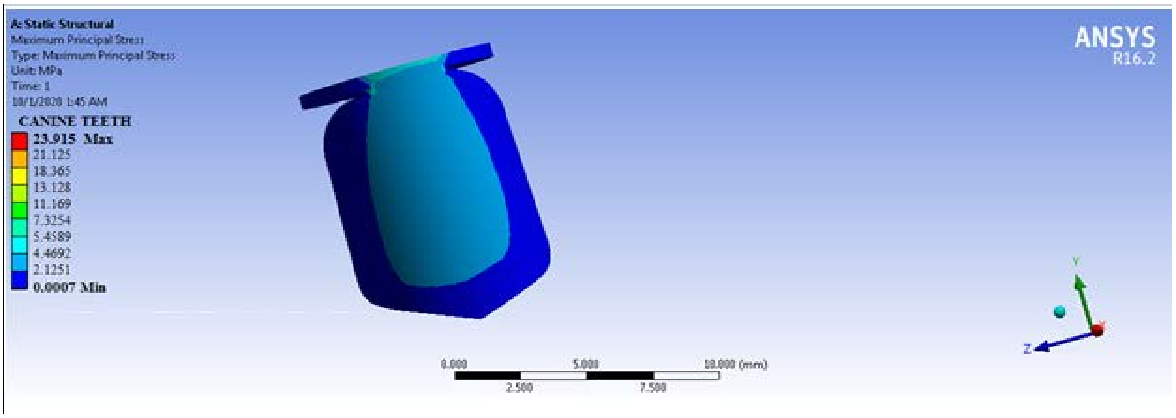
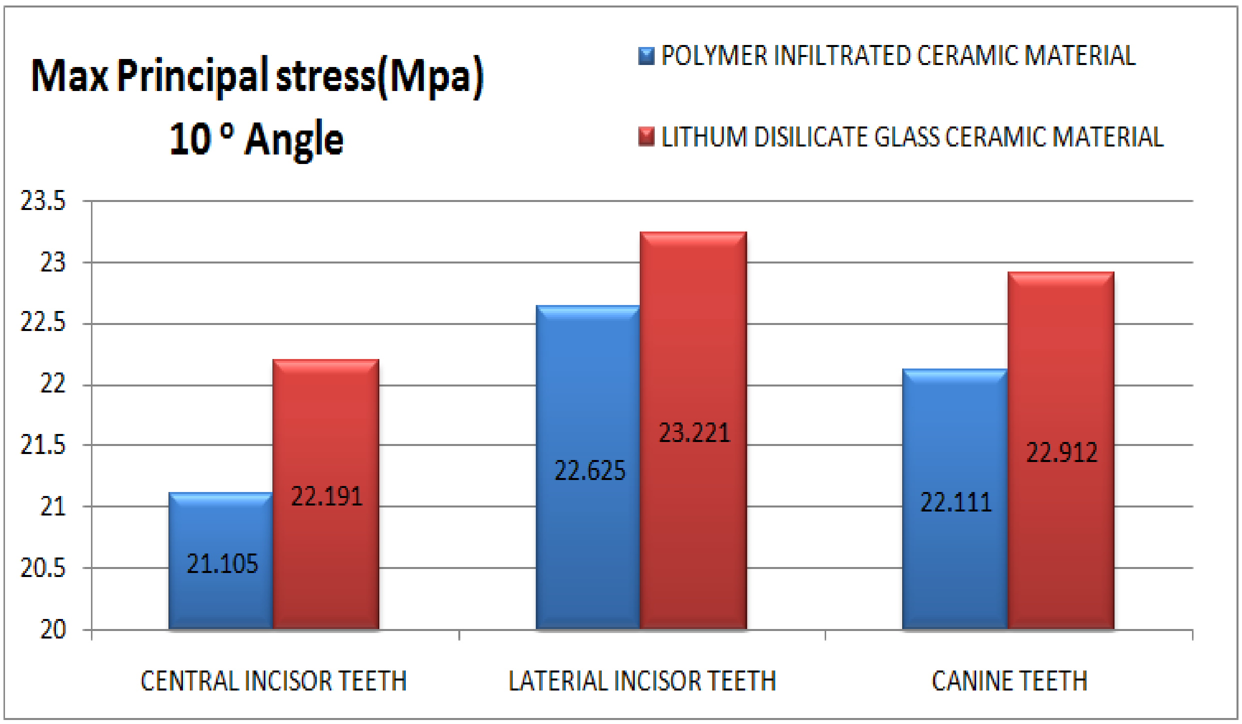


Fig 35: maxillary canine

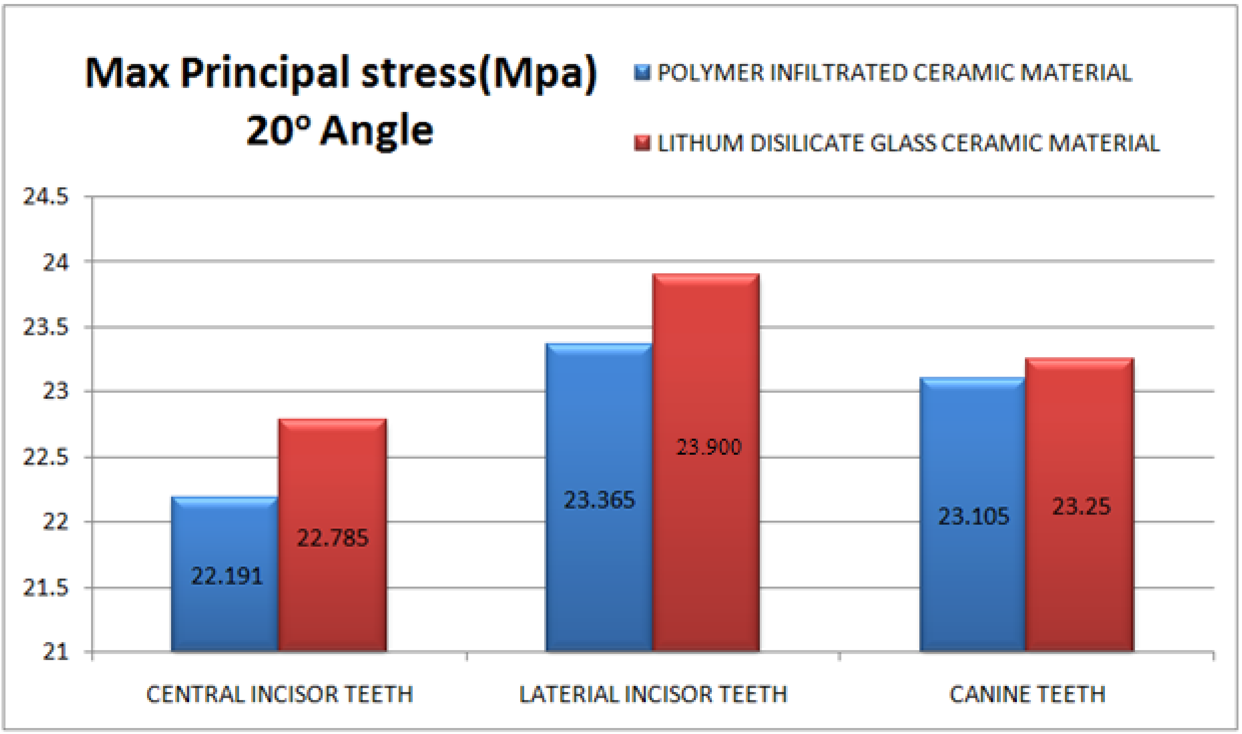
Observation & results

The magnitude of maximal principal stress between Ten-Degree convergence angle of maxillary central, lateral incisor and canine restored with L.D and PIC CAD/CAM crowns



Graph 1

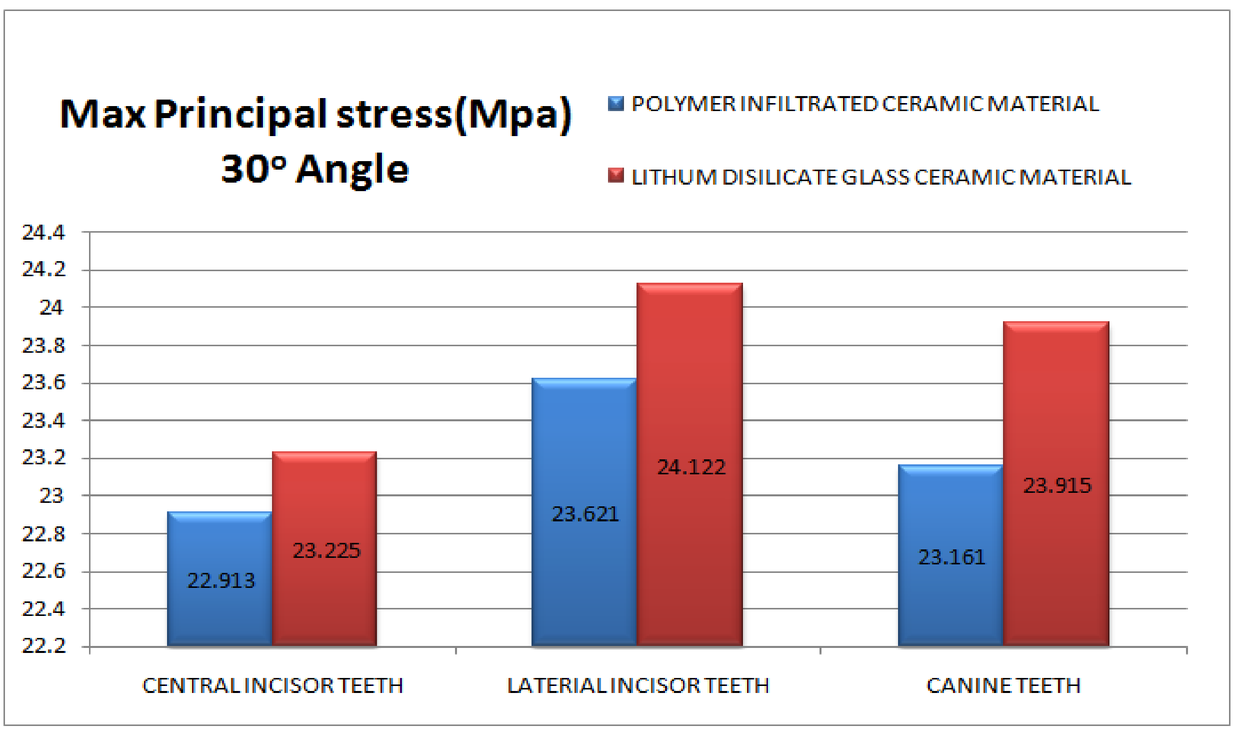
The magnitude of maximal principal stress between Twenty-Degree convergence angle of maxillary central, lateral incisor and canine restored with L.D and PIC CAD/CAM crowns.



Graph 2

Graph 2: Order of magnitude of stress when the load is applied is in the following order Lateral Incisor (L.D) > Lateral Incisor(PIC) > Canine (PIC) > Canine(L.D) > Central Incisor(L.D) > Central Incisor(PIC)

The magnitude of maximal principal stress between Thirty-Degree convergence angle of maxillary central, lateral incisor and canine restored with L.D and PIC CAD/CAM crowns



Graph 3

Graph 3: Order of magnitude of stress when the load is applied is in the following order Lateral Incisor (L.D) >Canine (L.D) > Lateral Incisor (PIC) > Central Incisor (L.D) > Canine (PIC) > Central Incisor (PIC)

Table 1: The maximum principal stress values of the ceramic crown in the preparation designs for three different tooth with two CAD/CAM crown materials

TOOTH	IPS e.max(L.D)(Mpa)	VIT. Enamic(PIC)(Mpa)
ClT10H	22.191	21.105
ClT10H	23.221	22.625
ClT10H	22.912	22.111

TOOTH	IPS e.max(L.D)(Mpa)	VIT.Enamic(PIC)(Mpa)
LIT20H	22.785	22.191
LlT20H	23.900	23.365
CT20H	23.250	23.105

TOOTH	IPS e.max(L.D)(Mpa)	VIT.Enamic(PIC)(Mpa)
ClT30H	23.225	22.913
LlT30H	24.122	23.621
CT30H	23.915	23.161