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Finite Element Analysis of Patient-Specific Maxillary Molar Crown

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Abstract: The Finite Element Method (FEM) is a numerical technique to seek out the solutions of partial differential equations. It absolutely was originated from the requirement of resolution complex geometry and structural analysis issues engineering field. FEM analysis has been widely used in engineering industries for many years. It is a vital tool to understand the mechanical behaviour of materials under completely different constraints. Now a day's medical industry is more relaying on the FEM-CAD solutions. Particularly for the dentistry, like CAD-CAM, the solutions of FEM are playing a vital role. This work is allotted to analyze the influence of various materials for the molar crown victimization FEM. As the human tooth is one of the complex structure geometries, the analysis of mechanical behaviour is more difficult. FEM can be useful for Orthodontics, Implantology, Restorative Dentistry and Prosthodontics. This work, the Finite element analysis is administered for the maxillary molar crown for the biocompatible materials such as metals, i.e. Cobalt chromium alloy and ceramics, i.e. Zirconia. The results are extremely useful for manufacturers of dental crowns and dentists.

Keywords*: *Dentistry, Dental Crown, FEM, Biocompatible materials

I. INTRODUCTION

The finite element method could be a numerical technique for finding the issues that area unit delineate by partial differential equations or is developed as purposeful minimization. A site of interest is pictured as an assembly of finite elements. The main steps of the finite element solution 1) Discretize the continuum 2) Select interpolation functions 3) Find the element properties 4) Assemble the element equations 5) Solve the global equation system 6) Compute additional results. Figure 1 indicates function interpolation of elements [20].

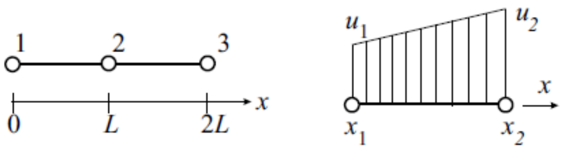

Figure: 1 Two 1-D linear elements and function interpolation inside an element

Finite Element method has been progressively employed in dental science in recent years. The results are helpful for Dentist and the manufacturer of Dental prosthesis to predict the behaviour of the biocompatible materials. In the manufacturing of Dental Implant, Crown and Bridges major materials are used till date are Gold alloy, Silver alloy, Cobalt-Chromium (Co-Cr) alloy, Titanium alloy, Zirconia and many more. These materials are biocompatible materials. This study is focused on the stress generated on the maxillary molar crown using ANSYS workbench (FEM tool) for the Co-Cr alloy and Zirconia biocompatible materials. FEM provides the amount of stress generated and displacement magnitude of the crown geometry for listed materials. In a dental science context, the interaction of jawbone and jaw teeth typically referred to as Bite, chew or Occlusion force. This force is made by the dynamic action of the masticatory system throughout the physiological act of chew. The finding from the previous literature gives the range of the bite force is varies from 100N to 800N for the molar teeth. By having the individual bite force, one can find the equivalent stress for different materials using FEM tool and material selection can be carried out.

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II. LITERATURE SURVEY

Literature survey is concentrated on FEA of the maxillary crown and the range of bite force.

N. de Jager describes about the FEA of stresses in dental crowns. The chew force is distributed evenly on the points of contact in occlusion, at 90° to the plane. The ensuring vertical (z) element was 665 N. After applying the load on crown, FEA simulation is carried out the result of equivalent stress. The crown is coated with porcelain it affects the strength of the materials [12].

Seung-Ryong Ha explains biomechanical three-dimensional finite element analysis of monolithic zirconia crown with different cement type. The objective of this study was to guage the influence of varied cement varieties on the strain distribution in monolithic oxide crowns below most bite force victimization the finite part analysis. For FEA, the researcher has considered the vertical load of 700N in Z-axis. The use of the monolithic zirconium oxide crowns has become standard within the restorative dentistry [13].

Yuanyuan Duan et al. describe effect of elasticity on stress distribution in CAD/CAM dental crowns: Glass-ceramic vs polymer–matrix composite. Here the Load applied at average human bite force (100 N) or most human bite force (600 N). Researchers have created one assumption that the dentine substrate and therefore the restorative materials were homogenized. The distribution of stress wasn't obsessed on the bite force, and Eccentric loading didn't well increase the utmost stress within the prosthesis [15].

Andréa B. Motta presented FEA for 2-Dimensional and 3-Dimensional models for sound and restored human teeth. The loading values used for the analyses range from 100N to 800N. 3D models of natural teeth have already been made and submitted to FEM analyses (ABAQUS) below physiological conditions [14].

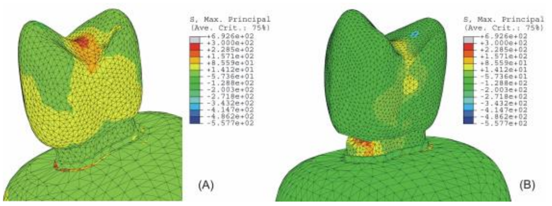

Figure:2 Maximum principal stress of the crown

Hae Ri Kim et al. explains on microstructures and mechanical properties of Cobalt-Chromium dental alloys fabricated by four different CAD/CAM-based techniques.

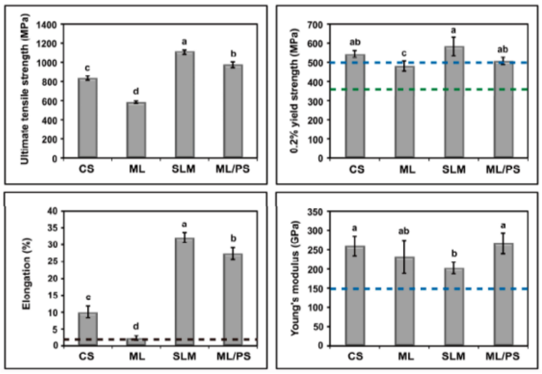

Figure:3 The comparison of mechanical properties of Co-Cr alloy.

The microstructures and mechanical properties of Co-Cr dental alloys made-up by four completely different producing ways which were investigated and compared to every different. The findings of this study clearly showed that the microstructures and the mechanical properties of the alloys, were greatly hooked into the producing techniques alongside the chemical compositions of the alloys used. Figure 3 shows the comparison of mechanical properties of the Co-Cr alloy specimens ready victimization the four completely different producing technique [21].

Bankole.I. Oladapo describes three-dimensional finite element analysis of a porcelain crowned tooth. The findings of this analysis are useful to investigate the stress distribution and localized vital points inside posterior crowns. it's price to say that the cut on surface tooth happens once the utmost load of 200 N engaged on the central incisors. The first model then exported into ABAQUS Finite Element tool for dental geometry analysis. [16].

Ya-Li Song et al. explains the feature-based posterior crown design in a dental CAD/CAM system the aim of building the quality prosthetic models is to get the reference profiles of the missing teeth. The preliminary thought for feature-based modeling is that each tooth has each complicated and special options. These options of the various teeth used for describing and dominant the topological construction utilizing geometrical ways square measure at first summarized supported gross anatomy. during this paper, a three-dimensional scanner is employed to amass the info of the standard tooth. The noninheritable information exist within the variety of separate points [22].

Amanda Maria et al. explains CAD-FEA modeling and analysis of different full crown monolithic restorations. To investigate the influence of various materials for monolithic full posterior crowns using 3-Dimensional analysis. The applied load is 600N. Additionally, most shear stress criteria were used for the cementing line. On the opposite hand, materials with lower modulus permit stress passage for cement, increasing shear stress on this layer. because the conclusion stiffer materials promote higher stress peak values. [17].

Qianzhou Jiang et al. described biomechanical properties of first maxillary molars with different endodontic cavities using a finite element analysis.

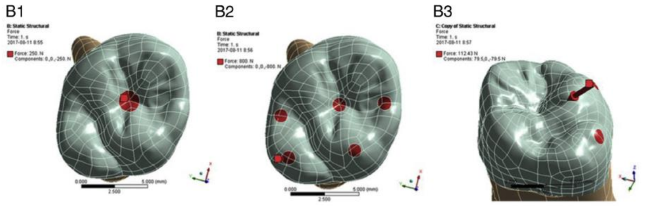

Figure:4 Different Loading conditions

In this study researcher had considered three different load conditions as shown in the above figure:

1. The models received a vertical force at a relentless intensity of 250 N. The load was applied to the central groove area of the model.
2. A force of 800 N was applied to 5 completely different points.
3. A force of 225 N was applied to the lingual plane of the lingual cusp at 45° to the longitudinal axis of the tooth, that was allotted 2 points [23].

Zhongpu Zhang et al. explains mechanical benefits of conservative restoration for dental fissure caries. In the study, a comparatively new computational approach, specifically XFEM, that has been implemented within the industrial code ABAQUS, was adopted. it has been shown that XFEM allows associate degree automatic simulation of crack initiation and propagation underneath the assumptions of linear elastic fracture mechanics (LEFM). The critical loads to initiate fracture obtained from the four totally different models thought about within the 2-Dimensional analyses were additionally summarized within the lower half [24].

The rigorous literature survey concludes the different methodology to select the material for a patient-specific molar crown applying FE analysis. The problem statement is to identify the biocompatible material for molar crown using finite element analysis. The analysis provides the values of equivalent stress and displacement for materials: Zirconia and Cobalt-Chromium alloy.

Methodology

The process flow for static structural FE Analysis of the patient-specific maxillary molar crown is as follows:

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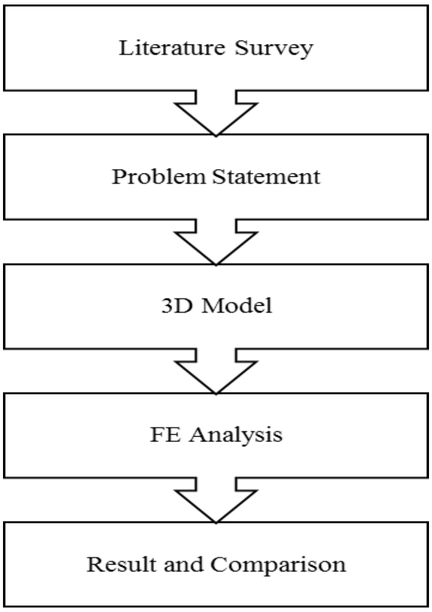

Figure:5 Process flow of Static structure analysis for molar crown

At the stage of FEA, one needs to select the biocompatible material for the structural analysis. Generally, the materials used as the dental crown are Gold alloy, Silver alloy, Titanium alloy, Cobalt-chromium alloy, Zirconia and many others. These are biocompatible and ductile materials. These materials are corrosion resistant and not reacting with the human body.

The first material used for this study is metal-Cobalt Chromium (Co-Cr) alloy with mechanical properties are as follows:

Table: 1 Mechanical Properties of Co-Cr alloy [18]

Sr No.	Properties	values
1	Density	8.5 g/cc
2	Tensile Strength	903-1070 MPa
3	Poisson's ratio	0.3
4	Modulus of Elasticity	230 GPa

Cobalt-Chromium alloy having more tensile strength and high modulus of elasticity. Another material used is a ceramic material-Zirconia. Zirconia is appearing like a human tooth. It is a bit costly than the metal alloy (Cobalt-Chromium alloy). The mechanical properties of the same are given to the below table:

Table: 2 Mechanical Properties of Zirconia [19]

Sr. No.	Properties	values
1	Density	5.6 g/cc
2	Tensile Strength	600-700MPa
3	Poisson's ratio	0.31
4	Modulus of Elasticity	200 GPa

For the static structure analysis of patient-specific 2nd maxillary molar crown, the maximum load is to be considered as 700N in the FEA tool- ANSYS workbench. The model is imported from the 3D Scanner for structural analysis with .stp (STEP format).

Steps of Finite element process as following:

1. Pre-process of FEM to import the 3D model:

Below figure 6 shows the 3D model of maxillary 2nd molar crown imported from 3D Scanning device and it is in .stp format.

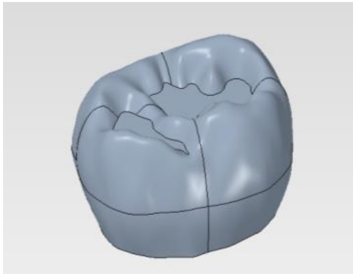

Figure:6 3D model of maxillary 2nd molar crown

2. The next step is to create meshing of the 3D Model.

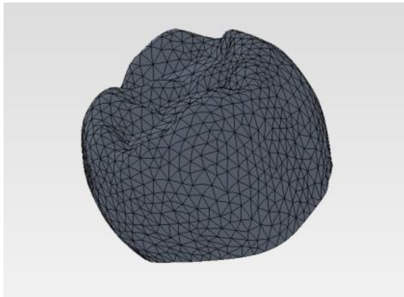

Figure:7 Meshing of maxillary 2nd molar crown

Meshing process divides the full element into the small elements. The shape of the elements used is tetrahedron. The number of elements: 36,271 and 52,214 nodes.

3. After generating a mesh, further step is to apply physical constraints such as fix support and load.

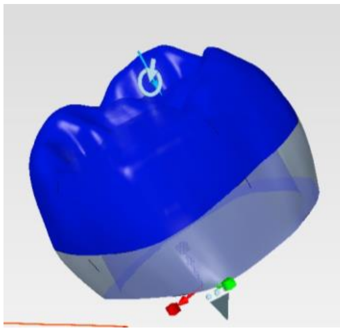

Figure:8 Load applied in the Z axis ranging 100N to 700N and fixing the base of maxillary 2nd molar crown

As shown in the figure 8, the base of the crown is fixed as it is restored with cement and the applied load on the crown in "Z" axis. The analysis is carried out for the load range of 100N to 700N for both biocompatible materials Cobalt chromium alloy and Zirconia.

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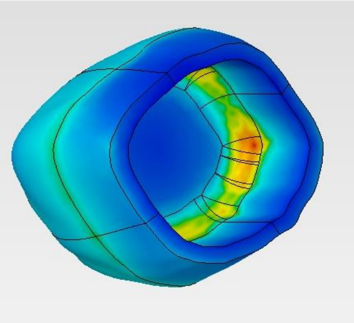

Figure:9 Equivalent stress of molar crown

Above sample image (figure 9) shows the effect of equivalent stress for the molar crown. After obtaining the results of equivalent stress for both materials, another analysis carried out to find the displacement magnitude. Figure 10 shows the result for the displacement magnitude for maxillary 2nd molar crown.

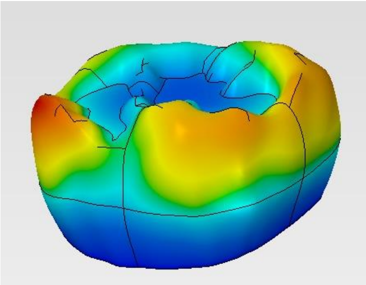

Figure:10 Displacement magnitude of molar crown

Finite element analysis is useful to describe the behaviour of biocompatible material under the static load condition.

III. RESULT AND DISCUSSION

The FE analysis taken up for two biocompatible materials Cobalt-chromium alloy and Zirconia to select the material for manufacturing of the molar crown. In the static structure analysis, the constraints are: 1) Fixing the base of molar crown 2) Appling the load of 100N to 700N with interval of 100N in the Z axis. Total 14 analysis taken up to find the equivalent stress and displacement magnitude of the dental crown. The result of static structure analysis are as follows:

Table:3 Result for Equivalent stress of molar crown

Sr. No.	Applied load in Z direction. (N)	Equivalent stress (N/mm^2)	
		Co-Cr alloy	Zirconia
1	100 N	1.81	1.78
2	200 N	3.63	3.5
3	300 N	5.4	5.3
4	400 N	7.26	7.2
5	500 N	9.07	9
6	600 N	10.89	10.88
7	700 N	12.7	12.6

Table:4 Result for displacement magnitude

Sr. No.	Applied load in Z direction. (N)	Displacement magnitude (m)	
		Co-Cr alloy	Zirconia
1	100 N	2.44×10^{-8}	2.82×10^{-8}
2	200 N	4.89×10^{-8}	5.65×10^{-8}
3	300 N	7.34×10^{-8}	8.4×10^{-8}
4	400 N	9.79×10^{-8}	1.13×10^{-7}
5	500 N	1.22×10^{-7}	1.41×10^{-7}
6	600 N	1.46×10^{-7}	1.69×10^{-7}
7	700 N	1.71×10^{-7}	1.97×10^{-7}

The results shows equivalent stress and magnitude of displacement increases as load increases. Result table compares the values of equivalent stress and displacement magnitude for the same load conditions — the mechanical properties such as density, modulus of elasticity and poisson's ratio effects the results. FEM results are helpful for the selection of biocompatible materials to fabricate the patient-specific molar crown.

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