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Three-dimensional finite element analysis of a porcelain crowned tooth

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ABSTRACT

The restoration of endodontically treated teeth is one of the main challenges in restorative dentistry since the weakened tooth structure is more prone to biomechanical failures due to significant tooth loss. The aim of this paper is to computational analysis of prepared crowned tooth in order to differentiate the possibility of using porcelain material for typical clinical condition and masticatory load by using the three-dimensional finite element method (3D FEM). In order to have an accurate geometry of tooth model, a coordinate measuring machine (CMM) is proposed to scan the tooth. The obtained scanned contours exported to ABAQUS FE package for computational stress analysis. The prosthodontics crown FEM has been created and put on simulated chewing stresses. The model is composed of four different materials, namely; prepared tooth, luting cement, substructure (IPS Empress Core), and Ingot (IPS Empress Layer). The generated FEM run and the stress distributions of the crowned tooth is thoroughly investigated. The developed model is extremely useful for indicating tooth biomechanics and has the tendency to deliver a better understanding to designers in the biomedical engineering field and dentistry.

1. Introduction

There are various reason for tooth damage such as carious or non-carious tooth surface loss. Caries is a bacterial infection of tooth that can happen due to special kind of bacteria in the mouth, which process sugar and release acid and attack teeth. Aging is another natural causing of tooth surface loss (non-carious), however, in some people wearing of teeth happens due to grinding or clenching habits at nights (Mohamed et al., 2015; Geng et al., 2001). Furthermore, chipping and accidental tooth breakage occurrence is other cause of non-carious tooth surface loss (Lakshmi et al., 2015). When a substantial amount of tooth structure has been lost due to fracture, caries or a large old filling that has failed; crowns are often used to restore a tooth. Crowns are types of dental restoration that cover all or the greater part of a tooth and cements permanently in place to become the new outer layer of the tooth. Patients are able to regain functions, speech correction and aesthetics by the help of different types of crowns. Crown is not only strengthening a damaged tooth, but also it improve the appearance, shape and alignment (Thompson et al., 2011).

In recent years, for crown or bridge construction, variety of material are available such as plastic (acrylic), metal, and porcelain. Many patients prefer all ceramic crowns to metal fused porcelain crowns due to good esthetics, biocompatibility and chemical durability (Pol-Christian and Kalk, 2011). Both crowns and bridges are fixed prosthetic appliance. Unlike removable devices such as dentures, which you can take it out and clean daily, crowns and bridges are cemented onto existing teeth or implants, and can only be removed by a dentist. Therefore, the working life of it is very vital. There are number of factors to contribute to crown performance. It is important suitable understanding of the variables affecting the mechanical behaviour of crowned tooth. Prediction of most likely fracture location and magnitude and distribution of stress associated with various types of restorations is of importance to the successful production of durable ceramic restorations.

Nowadays finite element model (FEM) is recognised as one of the great tool used in many fields of engineering for analysis, modification, or optimization of a design (Zahedi et al. 2013a,b; Shamsi-Sarband et al. 2012). This technique is now being used extensively in biomedical engineering in applications ranging from customized design and mitigation of different mechanical component and structures, visualization, geometric modelling and analysis of functional behaviour of materials (Mohamed et al., 2015; Afolabi et al. (2018); Bankole et al., 2015a). Many researchers have been trying to use these packages in dental technology with the hope of production higher and more uniform quality materials for dental treatment, customized medical implant

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design, standardizing manufacturing processes and reducing production costs. Seung-Ryong et al., 2016 evaluated the effect of coping design on the stress distributions in posterior zirconia crowns under various loads by FEM tool. The same study also perfumed by other researchers (Ha et al. 2013; Bankole et al., 2015b; Ijagbemi et al., 2016).

The geometrical shape of the human tooth is highly irregular and always is a challenging to create a highly details geometrical model. In addition, the distribution of different materials of the crowned tooth structure does not display any symmetry. While FEM has capability to predict the resistance of coatings and provide an important information of stresses generated in teeth and restorations, 3-dimensional modelling with the real dimensions is desirable in order to accomplish a reliable analysis. It is quite debated topic in the recent literature. Conventionally, a combination of manual description and cross-sectional images were implemented to acquire the geometry of complicated objects like a tooth structure (Tajima et al. 2009; Magne, 2007). In the crowned tooth model, due to the complexity of the anatomical shape and layered structure of the coating, the traditional methods for collecting surface contour are not precise. In fact, the tooth geometry is often grossly oversimplified, or converted to a two-dimensional model, which may compromise the reliability in determining the mechanical behaviour of the subject.

The purpose of this research is to analyse the stress distribution and localized critical points within posterior crowns with IPS empress coating type. Since anatomy of human teeth, have complex geometry a three-dimensional coordinate measuring machine (3D CMM) with the precision of 5 µm is used to generate an accurate three-dimensional solid model. Computer aiding design technology is used to translate the three-dimensional model form 3D CMM into ABAQUS finite element package for analysis. To determine actual stress results that are more reliable, layers of IPS empress core, IPS Empress Layer, over abutment tooth are generated for 3D FEM. The isotropic and homogenous material properties are assigned for simulation. The mechanical response of developed model of the crowned tooth is thoroughly deliberated under static loading condition. The obtained results then are studied using visualization software within the FEM environment to view a variety of parameters, and to fully identify implications of the analysis.

2. Finite element model description

The first step to develop FE model is to create a 3D tooth geometry from prepared crown tooth. The CMM Mitutoyo Euro C 9106 is used to measure the crowned tooth contour. The machine used is presented in Fig. 1. It has capability of axis move 900 mm toward X-direction, 1000 mm in Y direction and 600 mm Z direction with the resolution of

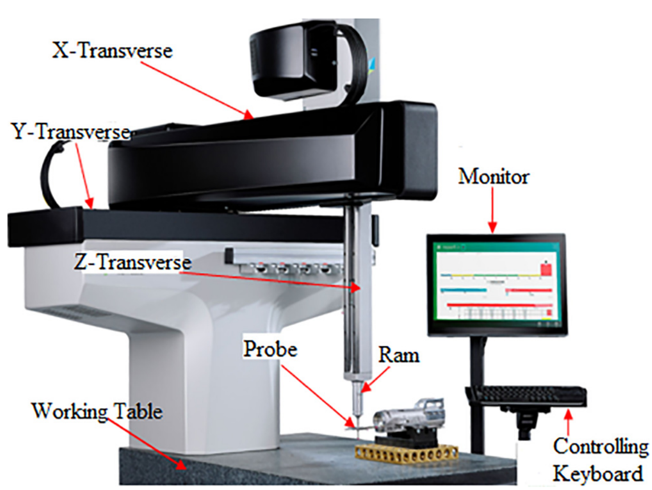

Fig. 1. Three-dimensional measuring instrument-Mitutoyo Euro C 9106.

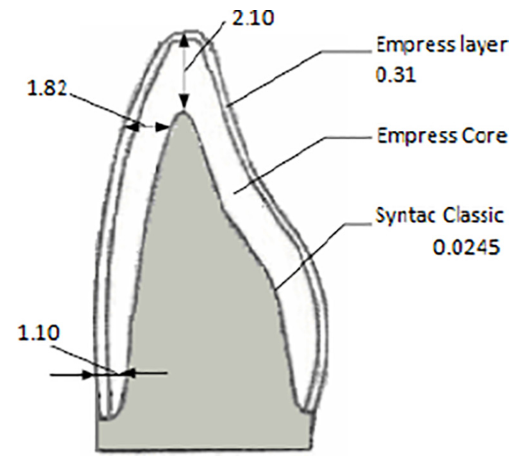

Fig. 2. Forming layers and relevant thicknesses of crowned model (dimension in mm).

5 µm. Crowned extracted first mandibular molar tooth of 44 years old female patient provided by Family Dental Care Centre in Nottingham was taken into account for this study. The geometry of teeth before and after crowned are measure by sensing discrete points on the surface of the teeth with a mechanical probe. The probe position controlled automatically by a computer and generated a cloud date points which were connected to form the surface models of primary tooth. The primary 3D points contour with IGES format then passes to ABAQUS professional series FE software for stress analysis.

The schematic of the crowned tooth model is shown in Fig. 2. The forming model contains four components. Prepared tooth, luting cement, substructure (IPS Empress Core) and Ingot (IPS Empress Layer). Empress is a new technology for manufacturing of porcelain crown that produce a teeth cover almost similar to natural teeth. Since the metal is not use for all ceramic crowns, it has great interest of use in anterior teeth for translucency and natural beauty. The thickness of the cement between the prepared tooth and the crown is taken to 245 µm. The first layer of crown, IPS Empress Layer has 0.31 mm thickness, and is applied on the second crown layer, IPS Empress Core. The lateral intervals of Empress Core started with 1.1 mm at the base, increased to 1.82 towards the upper part of tooth, and reached 2.10 mm at top tooth. A kinematic tie contact algorithm that allows stable computations without distortion is bounded interface of layers.

The tooth combine of many curved surfaces and therefore, to analyse the medial part accurately the model needs to partitions. Fig. 3a is shown the FEM of tooth consisted of 16 partitions. Based on an initial mesh-sensitivity analysis, the specimen is meshed with 854,380 s order parabolic tetrahedral elements. A mesh with a minimum element size of 0.12 µm was sufficient to characterize accurately the tooth stress. A fixed displacement and rotation constrains each of the nodes located at the most external part of the cortical bone supporting the restored tooth. It is considered a realistic boundary condition capable of providing an optimum prediction of stress state in the cemented machined all crown. The upper tooth modelled as a rigid material and used to guide the contacting force. The vertical load of 200 N is delivered by upper tooth to simulate physiologic masticatory forces. This force distributed uniformly perpendicular to the surface of crowned tooth (Fig. 3b). Surface to surface contact algorithm is developed for computational modelling. It is worth to mention that the cut on surface tooth happens when the maximum load of 200 N acting on the central incisors (Himmlova et al., 2004). For simplification of analysis, the static load is considered in this study while cyclic load with different magnitude is applied to the maxillary central incisors in the oral cavity.

One of the most critical factors that affect the part of the stress distribution under load is the mechanical properties of the materials used. Table 1 show the details of material properties of different

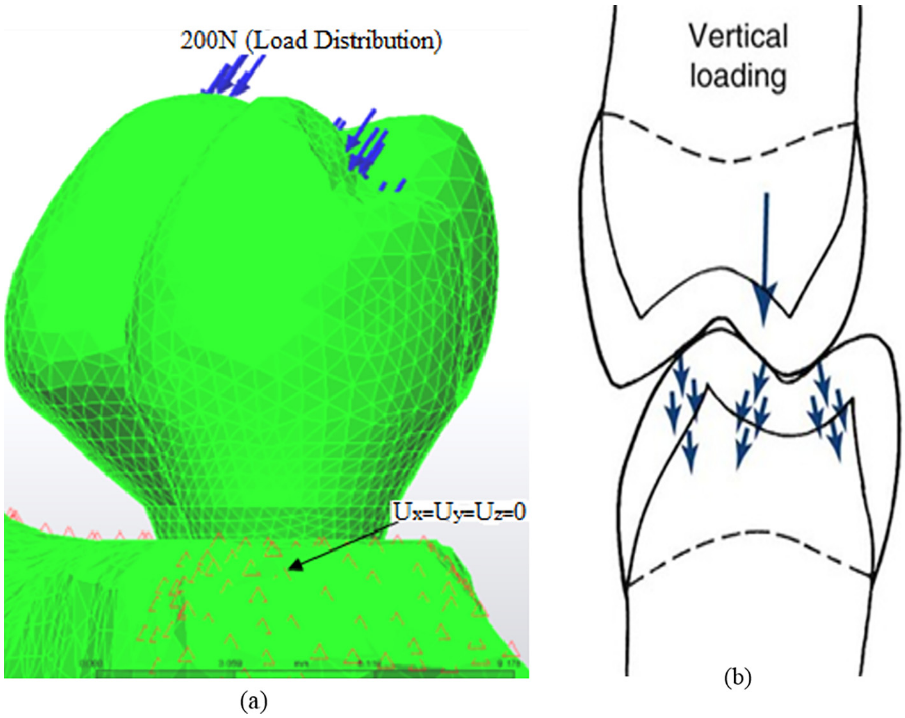

Fig. 3. Three-dimensional finite element model (a) and schematic view of vertical loading into crowned tooth (b).

Table 1
Material properties of crowned layers (Pekbey and Kiral, 2008).

	Young Modulus (MPa)	Shear Modulus (MPa)	Bulk Modulus (MPa)	Poisson ratio
Prepared teeth	1.860×10^4	7099.22	1.632×10^4	0.31
Luting cement	8300	3346.77	5320.51	0.24
IPS Empress Core	9.5×10^4	3.8×10^4	6.33×10^4	0.25
IPS Empress Layer	6.0×10^4	2.4×10^4	4.0×10^4	0.25

physical layers used for modelling of a crowned tooth based on exciting literature (Pekbey and Kiral, 2008). In this research, the material properties assume to be isotropic, homogeneous and linear elastic. The anisotropy of the crown and the tooth were not considered here.

Table 2
Maximum stresses and strains for each tooth layers.

	Max. Von Mises Stress (MPa)	Max. Shear Stress (MPa)	Max. Strain
Prepared teeth	5.7689	3.389	1.516×10^{-4}
Luting cement	11.489	3.297	2.526×10^{-4}
IPS Empress Core	22.985	13.289	1.517×10^{-4}
IPS Empress Layer	34.266	16.578	2.529×10^{-4}

However, because of the structure, the mechanical properties of tooth do vary with orientation and location.

3. Stress analysis results

The stress distribution within the treated tooth restored is multi-axial, nonuniform, and depends on the magnitude and direction of the

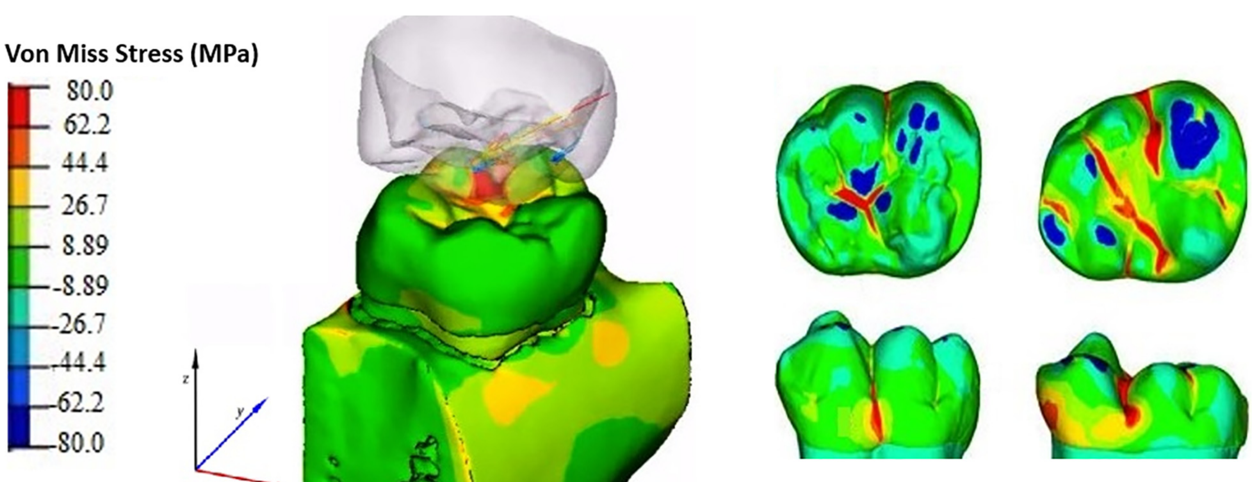

Fig. 4. Von Miss stress distribution of crowned tooth.

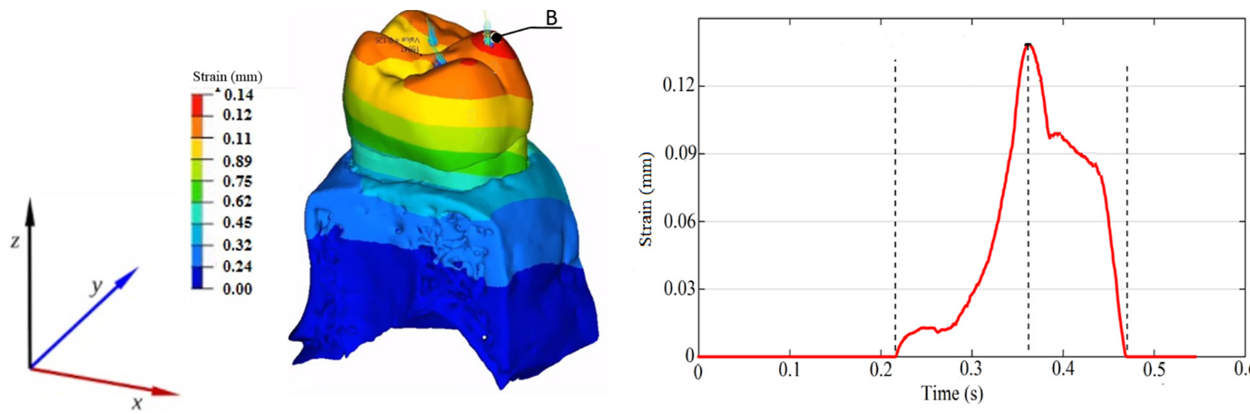

Fig. 5. Strain diagram at point B (tip of tooth) under contractin force.

applied masticatory forces. The Von Miss stresses value and patterns due to load application is presented in Fig. 4. The stress is visualised in colour coding ranging from dark blue (minimum stress) to red (maximum stress). The level of stress dissipate gradually after contact with the adjacent tooth from the pint of loading to the rest of crown. However, the maximum level of stresses are restricted to the crown with very little penetrating to the underlying tooth.

Table 2 is shown in details the maximum Von Miss stress, shear stress and strain recorded for each layers of tooth. The maximum Von Miss stress computed for prepared tooth is 5.76 MPa while in luting cement stress reaches to 11.489 MPa. The corresponding maximum share stress for both prepared tooth and luting cement are close and calculated to 3.373 MPa and 3.297 MPa, respectively. Stress value in the Empress Core and layer is higher than tooth core group, which can be attributed to the higher modulus of elasticity.

Fig. 5 is presented the strain history of point B (recorded as the highest strain point in the model) on simulated chewing. The total run time set to 0.6 (s). The highest strain magnitude of 0.126 mm happen at corresponding time of 0.362 s from staring job. This level of strain can lead to tooth fracture in the condition of greater force applied.

4. Conclusion

Dental biomechanics could be investigated more easily and more thoroughly by finite element analysis. Creating an accurate geometrical 3D restored tooth model is a challenging step for investigation. In this research, a 3D CMM is used to generate a precise 3D geometrical tooth model with varying cavities and restorative materials. The primary model then exported into ABQUS FE packages for dental structure analysis. A 3D model is constructed to more closely simulate a crowned tooth. The choice of crown material and crown thickness has a great influence on the stress distribution. The porcelain material applied in this study distributed a uniform stress to the root of the tooth and provided the region with more strength in a crowned tooth. The devolved model has tendency to deliver a better understanding of the crowned material to designers in biomedical engineering and medical personnel.

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