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Thermo-Mechanical Analysis of Restored Molar Tooth using Finite Element Analysis

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Abstract: The aim of the study is to find most optimum combination of crown material and adhesive to avoid loosening and thereby failure of restored tooth. This study describes the Thermo-Mechanical analysis of restored molar tooth crown for determination of the stress levels due to thermal and mechanical loads on restored molar tooth.

The potential use of the 3-D model was demonstrated and analyzed using different materials for crown. Thermal strain, stress and deformation were measured at hot and cold conditions in ANSYS and correlated with analytical calculation and existing experimental data for model validation and optimization. It is concluded that amongst various material porcelain crown with composite resin adhesive cement closely simulates the behavior of natural crown and should ideally result into long lasting restoration.

Keywords: Thresholding, Segmentation, Thermal strain, Dental restoration, Finite Element Method.

1 Introduction

The placement and replacement of crowns comprises a substantial portion of routine dental care provided in general dental practice. A recent review of the literature confirmed the view that dental restorations do not last forever. Over 60% of all restorative dentistry involves the replacement of restorations [Neil, Shaun, Ivar and Nairn (2003)].

As the human being consumes Tea, Coffee, Ice-creams, Cold drinks there is a temperature variation. These hot and cold conditions in the mouth create cyclic changes that could lead to thermal fatigue of the adhesive process. Different crown material with adhesive cements restorations promise to go some way towards the goal if their strength and accuracy of fit are adequate. A concern is that ceramics, although

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theoretically strong, tend in practice to be relatively weak, particularly under tensile loads [Toparli , Aykul and Sasaki (2003)].

Metal crown connected to the dental structure with adhesive cements are subjected to different mechanical loads. Additional interfacial stresses are subsequently superimposed by mechanical loading on the tooth during mastication and by the thermal loading at drinking of hot and cold liquids [Tulimar, Cornacchia and Estevam (2010)].

The objective of the study is to achieve most suitable combination of restoration material and the adhesive crown for long lasting treatment of fractured tooth. In the present paper, numerical analyses using the commercial finite element program ANSYS is performed for comparing the response of a sound human molar tooth with different crown materials restored directly with adhesive cements for thermal and mechanical loading. Initially, a simple geometry tooth model is analyzed to obtain the thermal loading due to temperature distribution at different temperature conditions and materials. Afterwards, the stresses arising from both thermal and thermo-mechanical loading are computed. The restoration–tissue interface is focused, where problems are observed in clinical practice.

The tooth is composed basically from enamel, dentin, pulp and cementum. Dentin and cementum have higher water and organic compound percentage when compared to the enamel and, due to this composition they are more susceptible to heat storage than the enamel [Denise and Patricia (2010)]. Dental pulp is a connective and vital tissue, and the higher vascularization makes this tissue strong susceptible to thermal changes.

Considering the thermal effect on dental hard tissues, it is necessary to know and to understand the thermal behavior of these tissues and crown materials when subjected to heating. Hence, the evaluation of the heat conduction phenomenon is extremely necessary. Several studies about thermal parameters measurement in hard dental tissues have been published [Boari, Ana, Eduardo, Powell and Zezell (2009)]. Results of these studies are summarized in Tab. 1. As the restored molar tooth is considered under thermal effect, initial calculations are done on simple geometry of molar tooth.

Calculation for thermal strain and stress [Bathe (2006)]

Thermal Strain= $\varepsilon^{th} = \alpha$ (T - T_{ref})

Thermal Stress= σ^{th} = E α (T - T_{ref})

For thin plate stress in Y and Z direction is zero.

Where E= Modulus of Elasticity (GPa), T= Temperature (^{0}C), T_{ref}= Reference temperature (37^{0}C), α = Coefficient of thermal expansion (x 10^{-6}/ ^{0}C).

Table 1: Mechanical and thermal properties of tooth tissue and crown material

Material/ Tissue	Density (x10^{-6Kg} /mm^3)	Thermal conductivity (x10^{-3}w /cm^0C)	Thermal expansion Coefficient (x$10^{-6}/^0C$)	Young's modu-lus (GPa)	Poisson's ratio	Tensile strength (M-Pa)	Compressive strength (MPa)
Enamel	2.97	9.34	16.96	84.1	0.33	45	385
Dentine	2.14	5.69	11	18.6	0.31	51	300
Bone	1.8	3	27.5	14.8	0.30	130	220
Steel	7.75	0.151	17	193	0.31	820	262
Porcelain	2.3	15	7.1	74	0.19	50	149
Ceramic	2.52	45	12.6	66.9	0.29	140	345
Resin	1.58	2.61	35	25	0.24	70	300

2 Methodology

Initially thermal analysis is carried out for different models of tooth assembly restored with various materials of crown. There were no significant results of thermal analysis and hence thermo mechanical analysis is carried out as per the flow chart given in fig 1. All the models are analysed for hot and cold load both. Analysis is carried out for healthy tooth, for tooth restored with steel crown, porcelain crown and ceramic crown. The crowns are normally cemented to the remaining tooth structure using different grades of adhesive cements. In the present study, composite resin and glass ionomer cements are considered since they are compatible with oral environment.

To begin with a simplified 3D solid model is constructed for FE analysis as shown in the fig 2 and the values are cross checked with the analytical values which are shown below. The mathematical model shown in fig 3 is based on the assumption that dentin and bone are parallel to each other and crown and dentin (tooth) are parallel to each other. The load is compressive in nature and acting in line with previous two assemblies.

The model shown in figure 2 is analysed for cold and hot load both. Following section shows only one set of mathematical analysis techniques for cold load on healthy tooth. The restored tooth models are solved when enamel is replaced with crown materials.

E stands for Young's modulus in MPa, A stands for Area of cross section, L is the length and α is the coefficient of thermal expansion.

Subscript B stands for bone, D_1 and D_2 stands for dentin parallel to bone and dentin part parallel to enamel respectively and E stands for enamel.

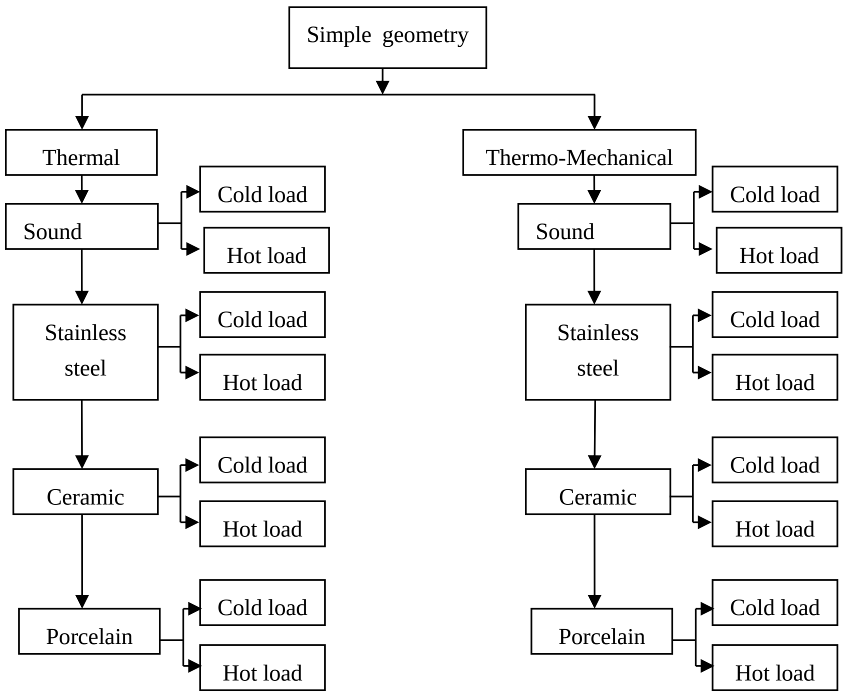

Figure 1: Sequential flow chart of analysis.

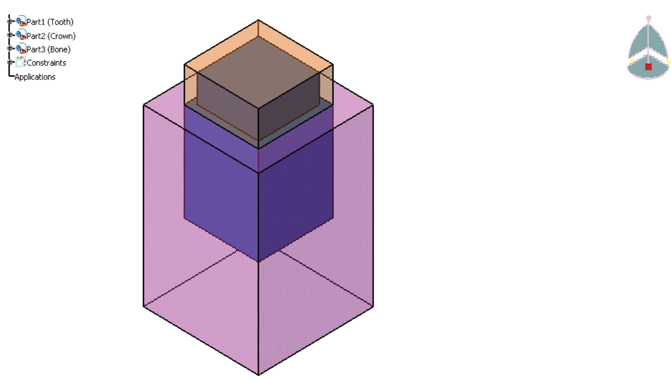

Figure 2: Simplified 3D model of tooth showing the assembly of enamel, dentin and bone.

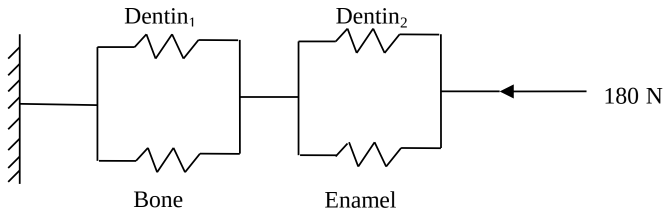

Figure 3: Free body diagram for tooth structure (cold)

$E_B = 14.8x10^3 \quad E_{D1} = 18.6x10^3 \quad E_{D2} = 18.6x10^3 \quad E_E = 84.1x10^3$

$A_B = 271mm^2 \quad A_{D1} = 154mm^2 \quad A_{D2} = 36mm^2 \quad A_E = 19mm^2$

$L_B = 25mm \quad L_{D1} = 14mm \quad L_{D2} = 4mm \quad L_E = 5mm$

$\alpha_B = 27.5 \times 10^{-6}/°\text{C} \quad \alpha_{D1} = 11x10^{-6}/°\text{C} \quad \alpha_{D2} = 11x10^{-6}/°\text{C} \quad \alpha_E = 16.96x10^{-6}/°\text{C}$

Stiffness matrix $K = \frac{AE}{L}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}$

$K_B = 10^3 \begin{bmatrix} 160.432 & -160.432 \\ -160.432 & 160.432 \end{bmatrix}$

$K_{D1} = 10^3 \begin{bmatrix} 204.6 & -204.6 \\ -204.6 & 204.6 \end{bmatrix}$

$K_{D2} = 10^3 \begin{bmatrix} 167.4 & -167.4 \\ -167.4 & 167.4 \end{bmatrix}$

$K_E = 10^3 \begin{bmatrix} 319.58 & -319.58 \\ -319.58 & 319.58 \end{bmatrix}$

$K_B + K_{D1} = 10^3 \begin{bmatrix} 365.032 & -365.032 \\ -365.032 & 365.032 \end{bmatrix}$

$K_{D2} + K_E = 10^3 \begin{bmatrix} 486.98 & -486.98 \\ -486.98 & 486.98 \end{bmatrix}$

$$K = 10^3 \begin{bmatrix} 365.032 & -365.032 & 0 \\ -365.032 & 684.612 & -319.58 \\ 0 & -319.58 & 319.58 \end{bmatrix}$$

Temperature Vector:

$$\theta_B = A_B E_B \alpha_B \Delta T \begin{bmatrix} -1 \\ 1 \end{bmatrix}$$

$$= 271 \times 14.8 \times 10^3 \times 27.5 \times 10^{-6} \times (4-37) \begin{bmatrix} -1 \\ 1 \end{bmatrix} = \begin{bmatrix} 3639.801 \\ -3639.801 \end{bmatrix}$$

$$\theta_{D1} = 154 \times 18.6 \times 10^3 \times 11 \times 10^{-6} \times (4-37) \begin{bmatrix} -1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1039.772 \\ -1039.772 \end{bmatrix}$$

$$\theta_{D2} = 36 \times 18.6 \times 10^3 \times 11 \times 10^{-6} \times (4-37) \begin{bmatrix} -1 \\ 1 \end{bmatrix} = \begin{bmatrix} 243.0648 \\ -243.0648 \end{bmatrix}$$

$$\theta_E = 19 \times 84.1 \times 10^3 \times 16.96 \times 10^{-6} \times (4-37) \begin{bmatrix} -1 \\ 1 \end{bmatrix} = \begin{bmatrix} 894.3126 \\ -894.3126 \end{bmatrix}$$

$$\theta_B + \theta_{D1} = \begin{bmatrix} 4679.573 \\ -4679.573 \end{bmatrix}$$

$$\theta_E + \theta_{D2} = \begin{bmatrix} 1137.3774 \\ -1137.3774 \end{bmatrix}$$

Global θ Matrix:

$$\theta = \begin{bmatrix} 4679.573 \\ -3542.1956 \\ -1137.3774 \end{bmatrix}$$

Global Load Vector:

$$\mathrm{P} = \mathrm{F} + \theta = \begin{bmatrix} 4679.573 \\ -3542.1956 \\ -1317.3774 \end{bmatrix}$$

P = KQ

$$\begin{bmatrix} 4679.573 \\ -3542.1956 \\ -1317.3774 \end{bmatrix} = 10^3 \begin{bmatrix} 365.032 & -365.032 & 0 \\ -365.032 & 684.612 & -319.58 \\ 0 & -319.58 & 319.58 \end{bmatrix} \begin{bmatrix} Q1 \\ \mathrm{Q2} \\ Q3 \end{bmatrix}$$

$Q_1 = 0$; $Q_2 = -0.013312$; $Q_3 = -0.017434$

Stress in bone

$$\sigma_B = \frac{E}{x_2 - x_1} \begin{bmatrix} -1 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ -0.013312 \end{bmatrix} - 14.8x10^3 \times 27.5 \times 10^{-6} \times (-33)$$
$$= 5.55148 N/mm^2$$

Strain in bone $= \in_B = \alpha_B \Delta T = -9.075 \times 10^{-4}$

Stress in dentine

σ_{D1}= - 10.9314 N/mm^2 $\sigma_{D2} = -12.3969 N/mm^2$, Strain in dentine $= \in_D = \alpha_D \Delta T = -3.63 \times 10^{-4}$

Stress in enamel

σ_E= - 22.1952 N/mm^2, Strain in enamel = $\in_E = \alpha_E \Delta$T = - 5.5968 x 10^{-4}

The results thus obtained for cold load and hot load are listed in the table 2. The results are verified with the results obtained from ANSYS, the finite element software. They are observed to be closely matching.

Table 2: Thermal strain and stress for ceramic crown

Result		Cold load (4°C to 37°C)	Hot load (37°C to 60°C)
ANSYS	Thermal strain	-0.000496	0.000227
	Thermal stress (MPa)	-31.139	13.717
Analytical	Thermal strain	-0.0004158	0.0002898
	Thermal stress (MPa)	-27.817	19.387

Hereafter the analysis is carried out for accurate model of tooth. Complete procedure for accurate modeling is explained in details. In this study a 3-D Finite Element (FE) model of a molar tooth is built using the MIMICS 9.11. The four layer model also includes a representation of the enamel, adhesive cement, dentine and bone, which is based on Computer Tomography (CT-scan) images. Different crown materials are considered with this model. Enamel, dentin and pulp are the basic tissues that constitute a sound human tooth. Stainless steel, Porcelain and ceramic are the restorative crown materials.

First the tooth is scanned with high resolution Micro-CT scanner. Second, the different hard tissues visible on the scans are identified using an interactive medical image control system (MIMICS 9.11). MIMICS imports CT data and allows extended visualization and segmentation functions based on image density thresholding shown in Fig. 4. 3-D objects (enamel and dentin) are automatically created in the form of masks by growing a threshold region on the entire stack of scans.

Figure 4: Three dimensional model of Molar tooth in MIMICS created from a CT scan.

The REMESH module attached to MIMICS is therefore used to automatically reduce the amount of triangles and simultaneously improve the quality of the triangles while maintaining the geometry shown in Fig. 5. After this .lis file can be imported in the finite element analysis software without generating any problem.

Third, .igs and .stp files are imported in CATIA software in order to re-establish the congruence of the interfacial mesh between enamel and dentin using Boolean operations (addition, inter section or subtraction of volumes). Then four layer molar tooth assembly model is prepared as shown in Fig. 6. Fourth, the .cat product files of the segmented enamel, dentin and bone assembly were then imported in ANSYS for the applying boundary conditions and attributing of material properties listed in Tab. 1.

Fixed zero-displacement in the three spatial dimensions was assigned to the nodes of bone at the bottom surface. The tooth and restorative materials were taken as bonded, which simulate usage of adhesive cements. Thermal analysis was performed, followed by analytical analysis. First, the initial temperature of the entire model was set to 37˚C, normal oral temperature of human body and thermal loads resulted from coefficients of thermal expansion. Case I is taken as cold load with extreme minimum temperature consumed by human beings as 4˚C whereas for hot

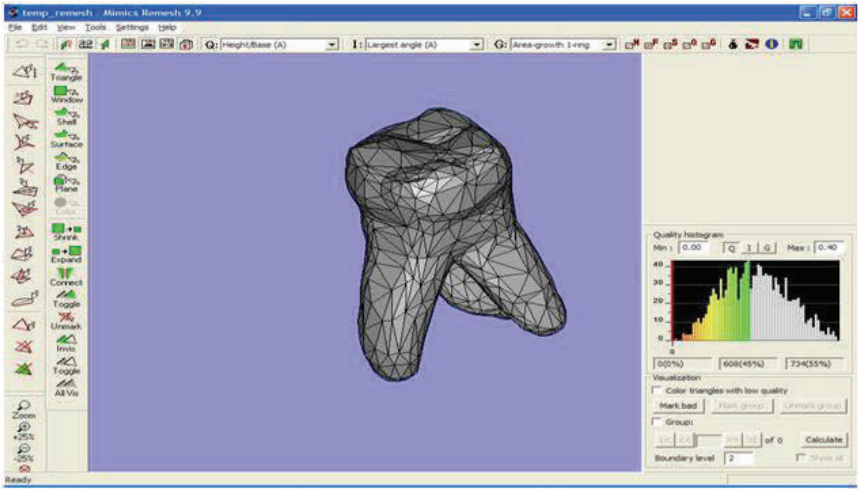

Figure 5: Remesh model of Molar tooth attached to MIMICS used to automatically reduce the amount of triangles and simultaneously improve the quality of the triangles while maintaining the geometry.

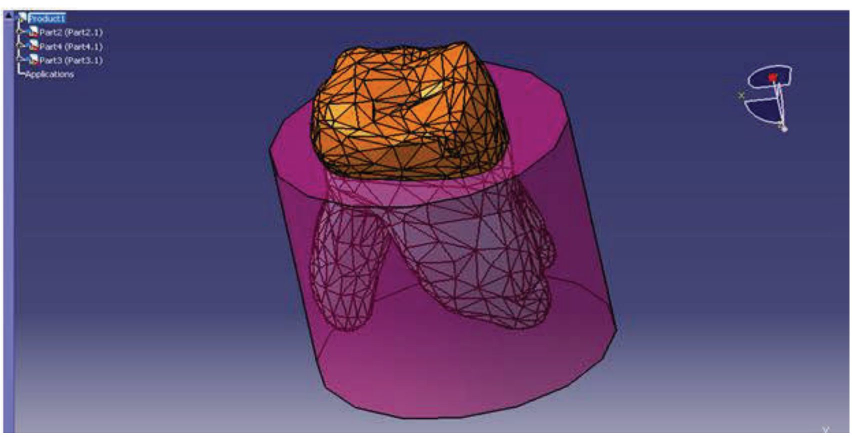

Figure 6: Molar tooth and bone assembly. Four layer assembly created using Boolean Operations is shown in the figure.

load the extreme maximum temperature is considered as 60˚C.

These temperature ranges were based on the work of Palmer, Barco, and Billy (1992) describing the temperature measured in the oral environment. Fig. 7(a) shows the finite element models used for both sound and restored tooth. In the sound human tooth, the restoration domain is considered enamel and for restored tooth different materials for crown is assigned.

In the steady state thermal analysis quadratic tetrahedral element is used for meshing. Thermal strain and stress distribution with temperature change were calculated as shown in Fig. 7(b). Tooth tissues and restorations were assumed to be isotropic, homogeneous and stress free when at a uniform temperature at 37˚C.

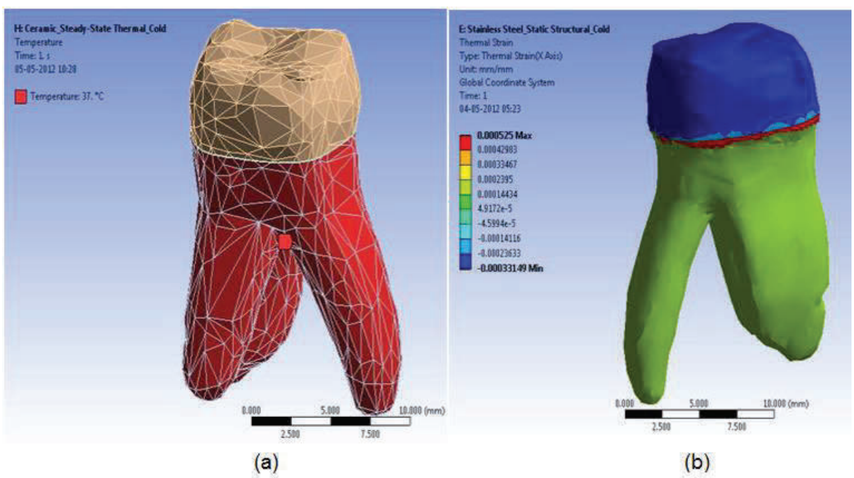

Figure 7: (a) The finite element model with the boundary conditions. Red area indicates the bone which is assigned with ambient temperature while the crown is subjected to extreme temperatures depending upon hot or cold condition. (b) Thermal strain distribution is shown in model of molar tooth assembly when subjected thermal loading only.

In next step, coupling of the effects of temperature variation and mastication loading is considered. To simulate mastication, vertical forces are distributed on the occlusal surface, using tetrahedral elements, representing the tooth behavior under mastication loading.

The mechanical load considered is 180 N, distributed over the crown in the occlusal contact points, as shown in Fig. 8(a). Tooth with different crown materials are compared to sound human tooth. The mechanical and thermal properties of each material and tooth tissue are assigned.

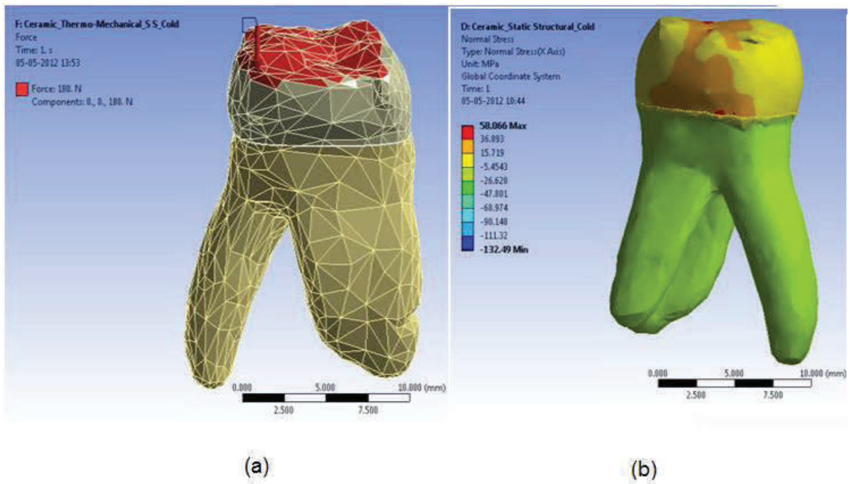

Figure 8: (a) Mechanical loading (180 N) distributed on molar crown at occlusal contact points while the bone is constrained for zero degree of freedom. (b) Stress distribution on molar tooth crown when subjected to thermal and mechanical loading both.

3 Results

Results corresponding to the four different models: sound (healthy) human tooth, metallic stainless steel crown restored with adhesive cement like resin, ceramic crown with resin and porcelain crown with resin are presented. Temperatures for cold condition varies from 4˚C to 37˚C and for hot condition varies from 37˚C to 60˚C taken for the thermal analysis. Under cold condition, tensile stresses appeared on the surface of the restoration and dental surface. However, in the internal structure, on the dentine-restoration interface, compressive stresses are verified as shown in Fig. 8 (b).

On the other hand, for hot condition, the opposite is verified: compressive stresses are found on the surface of the restoration and dental surface and tensile stresses are verified in the internal structure, on the dentine-restoration interface. Tab. 3 quantitatively summarizes these findings for thermal strain and normal stress in x-direction. It can be observed that the stress level found on the porcelain are lower than ceramic and stainless steel for this case.

Similar stress patterns are found for combined thermo-mechanical loading. The stress level found on the porcelain and ceramic are lower than stainless steel at this coupled load case as shown in Tab. 4.

Table 3: Thermal strain and stress for cold and hot condition

Temperature		Sound tooth	Stainless steel	Ceramic	Porcelain
For Cold 4°C to 37°C	Thermal Strain	0.0004125	0.000525	0.00051	0.0005
	Stress (MPa)	106.93	174.81	58.066	39.163
For Hot 37° to 60°C	Thermal Strain	0.0007192	0.000663	0.00051	0.0005
	Stress (MPa)	27.019	67.062	15.112	19.673

Table 4: Thermo-mechanical strain and stress for cold and hot condition

Temperature		Sound tooth	Stainless steel	Ceramic	Porcelain
For Cold 4°C to 37°C	Thermal Strain	0.00049	0.000525	0.00051	0.0005
	Stress (MPa)	84.643	166.24	53.308	34.864
For Hot 37° to 60°C	Thermal Strain	0.000662	0.000663	0.00051	0.0005
	Stress(MPa)	28.251	72.045	15.815	13.381

All the models are solved for both the adhesive cement materials as discussed in the flowchart. Table 5 demonstrates the results with resin and glass ionomer cements for porcelain crown.

Table 5: Thermo-mechanical strain and stress for porcelain crown with different cements

Temperature		Porcelain with Resin	Porcelain with Glass Ionomer
For Cold condition	Thermal Strain	-0.000138_{min} to 0.00052_{max}	-0.000138_{min} to 0.0004125_{max}
	Stress (MPa)	-109.11_{min} to 34.864_{max}	-143.44_{min} to 46.146_{max}
For Hot condition	Thermal Strain	0.000062_{min} to 0.000525_{max}	0.000062_{min} to 0.000412_{max}
	Stress (MPa)	-65.651_{min} to 13.381_{max}	-81.949_{min} to 28.659_{max}

4 Discussions and Conclusion

The thermal and mechanical stresses are essentially dependent on the deformations which are thereby dependent on the material properties. The superposition of tensile stresses due to the two effects, mechanical and thermal loads, in the adhesive interface can lead to cracking of the borders of the restorations, eventually resulting in micro leakage.

The finite element simulations showed that, under coupled thermo-mechanical loading, metallic crown result in higher stress levels than ceramic restorations. Therefore, clinical practitioners should keep this fact in mind when choosing the material for restoring teeth. The obtained results for hot and cold loading conditions are compared to results from analytical calculation. As to the numerical values for the obtained stresses, they should not be considered as exact, as the properties of dental tissues and restoring materials available in the literature have a wide range of variation, and tooth geometry also varies from individual to individual. Occurrence of maximum stress and thereby deformation at the crown-dentine junction results into loosening of crown which further leads to failure of restoration due to fatigue.

From this work, it can be concluded that simultaneous mechanical and thermal loading is a clinically relevant condition, which may contribute to tooth and restoration cracking. Under cold conditions, tensile stresses appeared on the surface of the restoration, while in the internal structure, on the dentin–restoration interface, compressive stresses were verified. On the other hand, for hot conditions, compressive stresses occurred on the surface of the restoration, and tensile stresses were verified in the internal structure, on the dentin–restoration interface. For cold condition stresses induced in tooth restored with steel is 200%, with ceramic is 63 % and with porcelain it is only 40 % of the natural tooth. For hot condition, stresses induced in tooth restored with steel is 250%, with ceramic is 53 % and with porcelain it is only 46 % of the natural tooth. Hence porcelain crown is the best choice for the restoration.

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