Annals Journal of Dental and Medical Assisting
2021, Volume 1, Issue 2, Page No: 8-16

Available online at: www.tsdp.net

ISSN: 3062-3510

Original Article

Study of Dental Bridges under Thermomechanical Loading

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Received: 30 May 2021; **Revised:** 30 October 2021; **Accepted:** 04 November 2021

ABSTRACT

In this study, the thermomechanical analysis of the three-dimensional model of the three-unit dental bridge in the area of the first and second premolars and the first molar of the lower jaw was performed in Ansys Workbench software. A dental bridge made of type 2 gold alloy and Lithium disilicate ceramic was exposed to fluid at 60 and 4 °C for 5 seconds on the chewing and lingual surface of the tooth. In addition, static load and shock load were applied in the middle of the dental bridge. The first static load was applied vertically and the second static load was applied obliquely at an angle of 45 degrees to the chewing surface and towards the buccal surface. The simulation of the impact force was carried out through the impactor with various kinetic energies perpendicular to the surface of the rodent. The maximum thermal stress created at 4°C was higher than at 60°C and was dependent on the thermal expansion coefficient, Young's modulus, and temperature field. In addition, the maximum thermal stress in the gold dental bridge was about 30% higher than the ceramic bridge. It was also found that in cases where only vertical forces are considered, the stress is predicted to be about 40% less than the oblique force. The stress severity under the rigid impactor with kinetic energy of 19.4, 8.6, and 2.2 mJ was calculated for the impactor as 3, 2.2, and 1.35 times the static stress, respectively, and the reaction force in the roots is proportional to the amount of impactor kinetic energy. Based on the results of this research, the stresses created in the dental bridge in cold thermal stimulation and impact loading are more critical than other loading modes. On average, ceramic dental bridges create less tension in dental bridges and tooth tissue.

Keywords: Bridges, Dental, Thermomechanical loading, Tooth

How to Cite This Article: Varghese JT, Islam F, Farrar P, Prentice L, Prusty BG. Study of Dental Bridges under Thermomechanical Loading. Ann J Dent Med Assist. 2021;1(2):8-16. https://doi.org/10.51847/G7fZF0n0yF

Introduction

Different methods of replacing missing teeth include the use of imbrigent, removable prostheses and different types of dental bridges. A bridge is a prosthesis that fills the space between two teeth. There are different types of dental bridges. The most common type is the fixed bridge, which consists of a crown on one or both sides of the artificial tooth or pontic. The crown is placed on the side teeth, which are called the base teeth. One of the problems and side effects of this type of bridge is that to place the crown, the base teeth must be shaved even though they are healthy [1, 2].

Eating and drinking causes thermal and mechanical load on teeth and dental restorations. The thermal load is caused by temperature change and the mechanical load is caused by the very complex contact patterns of the teeth of the two jaws and the different forces of the masticatory muscles during chewing and crushing food between the teeth of the two jaws. The design of dental restorations requires accurate determination of thermomechanical stress distribution and deformation in the form of clinical, experimental, and numerical methods. Laboratory studies that simulate oral conditions are expensive and it is not possible to calculate the parameters in the depth of tooth tissue in these studies. As an alternative method, finite element numerical simulation is a powerful method for evaluating the strength of restored teeth and has been widely used [3, 4].

In general, the important thing about temperature is that for the pulp to remain healthy, its temperature changes during the application of heat flux should be less than 5.5 °C [4]. Zach and Cohen [5] have reported pulp irreversibility of 15% at a temperature above 5.6 °C, 60% for a temperature of 11°C, and 100% for a temperature increase of 16.6 °C by studying monkey teeth. However, Baldissara *et al*. reported that increasing the pulp temperature from 8.9 °C to 14.7 °C in humans does not cause damage to it [6]. In addition, according to the studies of Eriksson *et al*. a temperature of 42 °C may be critical when maintained for 1 minute [7].

In the thermomechanical analysis section, temperature and stress distribution on the restoration of type 2 gold inlays and ceramic and composite [8], teeth restored with resin and porcelain [9], crown reconstruction using the placement of a prefabricated post in the root [10], bridge A tooth made of porcelain bonded to metal [11], an all-ceramic dental bridge made of zirconia, Empress 1, Empress 2, In-Ceram Alumina [12, 13] has been calculated under thermal load and static load. Static forces in the range of 150 to 400 Newton's are considered vertically and obliquely, mainly with an angle of 45 degrees on the chewing surface and towards the outside of the tooth, i.e. the buccal surface. According to the results, the stress created in the oblique load is more critical than the vertical load. The maximum tension in the dental bridge occurs in the connection areas between the pontic and the lateral crowns and the areas of the pontic connection to the lateral crowns and depends on the type of material [14-16]. In addition, thermal stress is less than mechanical stress and the tooth is more vulnerable to mechanical force.

According to the research conducted on the stress analysis on all types of dental restorations, in most references, the loading on the tooth is static and thermal. However, due to the inverse relationship between the amount of stress and the loading time, dynamic stresses damage teeth more than static stresses. However, few studies have investigated dynamic analysis. The dynamic load is mainly caused by chewing and crushing hard pieces of food between the teeth of the two jaws and is considered a time-varying force [17] or an impact load caused by an impactor with a certain initial speed [18, 19].

A few references have examined thermomechanical analysis on dental bridges [11, 14, 20, 21], and in particular, impact load analysis on dental bridges has been examined in only 1 study and as a time-varying force [20]. In this study, force changes with time have been assumed as a rectangular pulse function, and the amount of force and the duration of its application have been estimated. In the present study, the thermomechanical analysis of dental bridges due to thermal, static, and impact loading was investigated and compared using the finite element method. In addition, an impactor with variable kinetic energy has been used to model impact loading. The advantage of this method is that the software calculates the contact force and the duration of its application during the impact in a time-varying manner according to the mechanical properties and geometry of the two materials that are in contact with each other. The results of this research will provide a better understanding of the critical points and the destruction mechanism of dental bridges with different materials.

Materials and Methods

Modeling

In this research, a dental bridge made of Lithium disilicate ceramic and type 2 gold was selected. The dental bridge examined in this research was obtained from a 3D scan and was designed to replace the second premolar tooth in the lower jaw by preparing the first premolar and first molar teeth. After selecting the modeling parameters that include the mechanical and thermal properties of the materials used for dental bridges and dental components, numerical simulation was performed in Ansys Workbench software. In modeling the action of chewing and drinking hot and cold liquids, tooth components have elastic deformation, for this reason, the use of linear finite element analysis can provide useful information about the location of stress concentration.

After the initial meshing, a finer mesh was selected in the points with stress concentration, i.e. in the pontic connections to the lateral crowns and the grooves of the occlusal surface of the bridge crown. By calculating the displacement in the middle of the dental bridge in different mesh sizes, the independence of the mesh was checked and finally, the mesh size was 0.4 mm and 0.1 mm in the points with stress concentration. It should be noted that due to stress concentration, by making the mesh size smaller, the maximum stress increases continuously and never converges. For this reason, the displacement parameter has been used to check the independence of the mesh.

Loading and boundary conditions

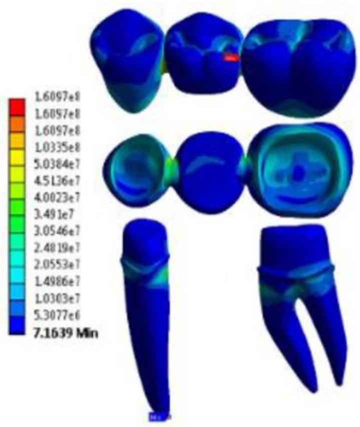
Thermal loading - the dental bridge was placed under the effect of convective heat transfer caused by exposure to hot and cold food at 60 and 4 °C for 5 seconds on the chewing or occlusal and hidden or lingual surface of the tooth. The temperature of the outer surface of the tooth due to contact with the skin and gums, as well as the temperature of the root of the tooth due to blood circulation, is considered 37 °C. The initial temperature of the tooth is also considered to be 37 °C. Heat transfer coefficients of 0.003774 and 0.0031568 W/mm°C have been used for eating ice cream and drinking milk, respectively. In addition, hot and cold stimulation temperatures are selected according to the fluid that is in contact with the dental bridge. Changing the fluid and its temperature affects the convective heat transfer coefficient and the results of temperature and stress distribution. Normally, the convective heat transfer coefficient increases with increasing temperature and is higher in warm excitation. In addition, the coefficient of heat conduction for solid bodies is lower than for moving fluid [22]. Therefore, by changing the fluid and its temperature, the presented results will change.

Static loading - Static loading is applied both vertically and obliquely on a small part of the occlusal surface of the pontic at an angle of 45 degrees to the chewing surface and towards the external or buccal surface of the tooth. According to the assumptions and results of previous research [23, 24], the vertical and oblique force is equal to 200 Newton's. Impact loading - Similar to previous studies [18, 19], the impact load was modeled through the collision of a rigid hemisphere with different speeds and specific mass. The interaction between the impactor and the bridge surface is assumed frictionless. The solid hemisphere with a diameter of 1.5 mm was tangential to the surface of the pontic tooth at the first moment and then hit the bridge vertically with an initial speed of 25, 50, and 75 m/s. The impactor rebounds after hitting the dental bridge. Because of changes in the linear momentum of the impactor, a contact force was created between the impactor and the dental bridge, which was applied in a very short time. It should be noted that the impactor's kinetic energy depends on its mass in addition to its speed. For all three thermal, static, and impact analyses, the fixed roots and the connection between the bridge crowns and the base teeth are considered full connection types.

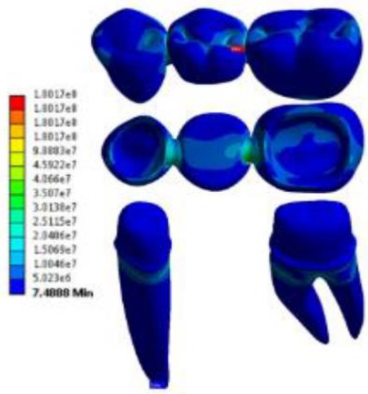
Results and Discussion

Thermal analysis results

Figure 1 shows the distribution of temperature and thermal stress in molar and premolar base teeth and a gold dental bridge in 5 seconds after hot and cold stimulation. The entry/exit of thermal flux into the dental bridge causes temperature change and its expansion/contraction, and as a result, thermal stress is created due to the difference in the thermal and mechanical properties of the restorative material and dental tissues. According to the results, the pattern of temperature and stress distribution is the same for gold and Lithium disilicate. For this reason, only the results of the gold dental bridge are given. However, the heat transfer from the surface to the dental pulp is greater in the gold dental bridge than in ceramic. Similar results have already been reported in the thermal analysis of restored teeth [1, 8]. The maximum thermal stress was created in the pontic connections to the side crowns, the grooves of the outer surface of the bridge, and the connection of the crown to the trimmed base teeth. These areas are vulnerable and prone to crack formation and growth.



a)



b)

Figure 1. Thermal stress distribution in megapascals in different parts of teeth and dental bridges made of gold exposed to convective heat transfer caused by eating a) hot and b) cold.

To check the tension more precisely, the maximum and minimum tension values in dental bridges in 5 seconds after hot and cold stimulation are given in **Table 1**. A restorative material that has less stress and more importantly, less stress on the dental tissues, is a more appropriate choice. The maximum thermal stress in tooth tissue and gold dental bridge at both temperatures of 4 and 60 °C is on average 32% higher than that of ceramic bridges. In addition, the maximum thermal stress created at a temperature of 4 °C is higher than at a temperature of 60 °C, which is the reason for the greater temperature difference in cold stimulation. If the strength of type 2 gold is within the strength range of Lithium disilicate ceramic, in the thermal stresses created according to **Table 1**, a dental bridge made of Lithium disilicate ceramic is a more appropriate choice to create less stress in the dental tissue.

Table 1. The results of thermal stress analysis of dental bridges of different types.

Material	The maximum tension in warm excitation with a temperature of 60 °C		Maximum tension in cold stirring with a temperature of 4 °C	
	Dental bridge (MPa)	Tooth texture (MPa)	Dental bridge (MPa)	Tooth texture (MPa)
Gold	0.161	1.65	2.180	0.31
Ceramic (Lithium disilicate)	6.117	7.51	3.148	6.34

Since the initial temperature of the tooth is 37 °C, when hot and cold thermal flux is applied to the chewing and hidden surface of the dental bridge, heat transfer from the bridge to ice cream occurs in cold stimulation, and heat transfer from hot milk to the bridge occurs in hot stimulation. Due to the temperature difference between cold and warm stimulation with the tooth surface, the heat flux is higher in warm stimulation. The coefficient of thermal conductivity affects the transient distribution of temperature and heat flux during different times and thus on the transient distribution of stress. The higher the thermal conductivity coefficient of the dental bridge, the higher its heat flux and temperature changes from the surface of the bridge to the center and then to the side teeth occur sooner. The coefficient of thermal conductivity of gold and lithium disilicate ceramic is about 4 and 2 times that of ivory, respectively. For this reason, the thermal flux is higher in dental bridges, especially in gold. In addition to the conductivity coefficient, the specific heat of the material also affects the temperature distribution in time. The specific heat of lithium disilicate ceramic is similar to that of dentin, but for gold, it is less than one-tenth that of dentin. Therefore, the time it takes for any very small volume of ceramic to have temperature changes is longer.

Another point that is very important in transient thermal analysis is the difference between the coefficient of thermal expansion of the restorative material and the tooth. If the restorative material and the tooth have the same coefficient of thermal expansion, they will not have different lengths due to heating and tension will not be created. Therefore, the greater the difference between the coefficient of thermal expansion of the tooth and the restorative material, the greater the thermal stress will be. The coefficient of thermal expansion of gold is higher than lithium disilicate ceramic. This confirms the higher thermal stress in gold dental bridges compared to ceramics, whose maximum value for gold is 1.28 times that of ceramics. Matching the results of flux and thermal stress changes from the finite element model with thermodynamic science is a confirmation of the modeling function. Another effective and important influencing factor in transient thermal stress is Young's modulus of the restorative material. The higher the elastic modulus of the restorative material, the more stress is created due to thermal expansion/contraction resulting from its cooling and heating, and the strain created in it will be equivalent to more stress. In this study, Young's modulus of lithium disilicate ceramic and gold is assumed almost equal. Finally, the four factors of thermal conductivity coefficient, thermal expansion coefficient, Young's modulus of the repair material, and specific heat are related in a complex way. For each examined sample, these four factors cannot be separated, and the only way to conclude thermal stress distribution is through numerical simulation.

Figures 2 and 3 show the graphs of maximum thermal stress and maximum thermal flux at different times. The maximum heat flux for hot and cold stimulation increases with time. After the temperature of the restorative material is completely changed, the longer the heating or cooling time on the tooth, the heat flux will not increase continuously. Because the tooth tissue also starts to change temperature, the temperature difference between the restoration and the tooth tissue decreases and reaches a constant value. Therefore, the heat flux has reached a steady state after 4 seconds. The maximum stress has also reached a stable state after 4 seconds for both hot and cold stimulation, and it is higher in gold than lithium disilicate ceramic. Similar results have been seen in previous research on the temperature changes of inlay, onlay, and imbrigent restorations [25, 26]. However, the maximum tension created in dental bridge restoration is higher, because it involves a significant part of the tooth, and as a result, the mechanical and thermal properties of the restoration will have a significant effect on the results.

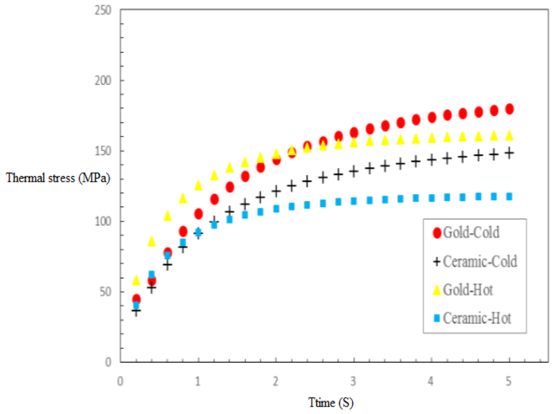


Figure 2. The diagram of maximum thermal stress changes from 0 to 5 seconds in two hot and cold stimuli for gold and ceramic dental bridges.

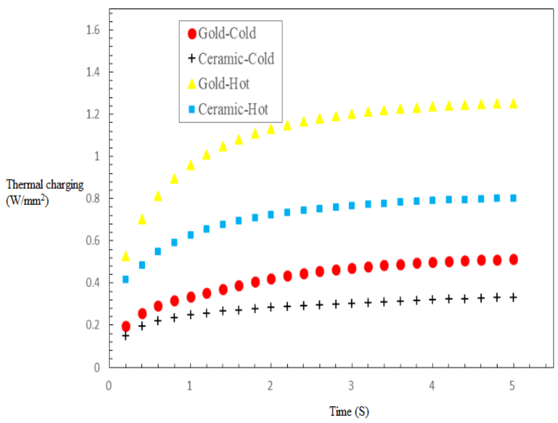


Figure 3. The diagram of the maximum heat flux changes from 0 to 5 seconds in two hot and cold stimulations for a dental bridge made of gold and ceramic.

The changes in extreme temperature distribution in terms of time are shown in **Figure 4**. Transferring heat to the depth of the tooth changes the temperature of the tooth core or pulp, which can cause irreparable damage such as irreversible inflammation. Therefore, less heat transfer to the pulp of the tooth is considered an advantage for the restorative material. In the current research, the temperature in the depth of the tooth reaches a stable state within 5 seconds, and for cold stimulation in the pulp area and near the crown for the gold and lithium disilicate ceramic dental bridge, it is in the range of 27-36 °C. While the temperature of the same area has increased in hot stimulation and is in the range of 37-45 °C. Therefore, according to the presented research, temperature changes compared to the initial temperature of the tooth, i.e. 37 °C, do not seem favorable. Of course, for more accurate modeling of temperature distribution and thermal stress, the cement used for gluing the bridge on the tooth crown and the tooth pulp should be modeled as a separate material. These two parts have a low thermal conductivity coefficient and high specific heat, which will reduce the heat flux and decrease the temperature changes in the area of the tooth core.

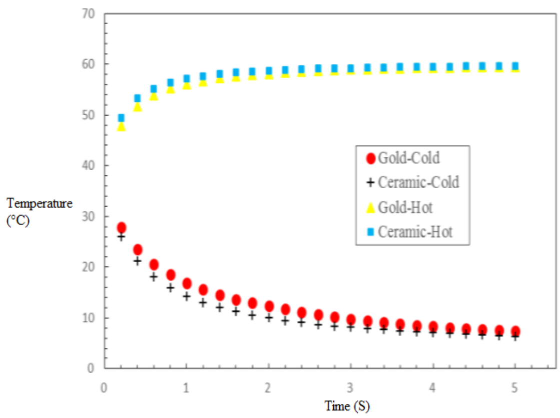


Figure 4. Graph of extreme temperature from 0 to 5 seconds in two hot and cold stimuli for a dental bridge made of gold and ceramic.

Static analysis results

The applied angle and force, as well as the material of the dental bridge, create different patterns of stress concentration in the pontic connection to the base teeth in the dental bridge, which is shown in **Figure 5** for the gold dental bridge exposed to oblique load. According to this figure, the stress distribution in the joints is not uniform and its maximum occurs on the outer surfaces, where the bending and torsional stresses are higher.

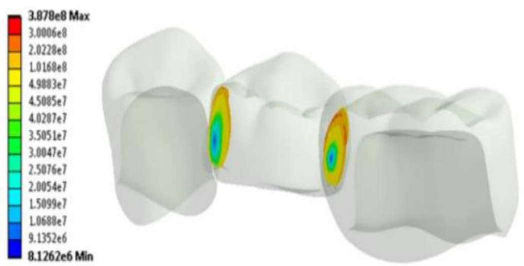


Figure 5. Von Mises stress in megapascals in dental joints and dental bridges subjected to oblique load on gold dental bridges.

Figure 6 shows the stress in megapascals for a gold dental bridge in oblique loading mode. The highest mechanical stress was created in the parts of the pontic connection to the side crowns, the bottom surface, and the occlusal surface of the bridge, which is the same in previous studies [21, 27, 28].

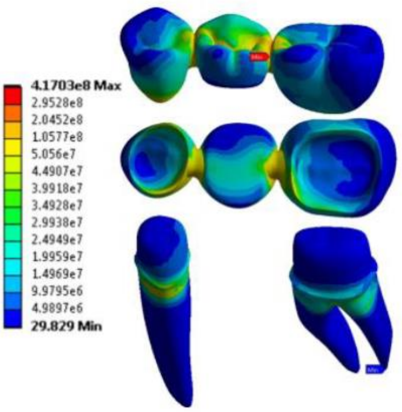


Figure 6. Von Mises stress distribution in megapascals in different parts of teeth and dental bridges made of gold material under inclined load.

Considering the linear elastic behavior of the bridge and dental tissue, stress and displacement will have a linear relationship with force. Since the oblique load causes biaxial bending and twisting in the bridge and side teeth, the amount of displacement and stress in the oblique load is more than the vertical load [29, 30] and the stress in the oblique load is about 40% more than the vertical load. However, in both inclined and vertical loading modes, the stress in the lithium disilicate ceramic bridge is slightly higher than that of gold. Unlike thermal stress, static stress in tooth tissue does not differ much in ceramic and gold bridge restoration. On the other hand, because the criterion of the maximum main stress is suitable for fracture analysis of brittle materials such as ceramics, the values of the main stresses are needed to estimate its strength, as shown in **Table 2**.

Table 2. Comparison of main stress values in terms of megapascals in impact loading, static load, and thermal load in ceramic dental bridges.

	Impact load	**Vertical static load**	**Inclined static load**	**Cold thermal stimulation exposed to fluid at 4 °C**	**Hot thermal stimulation exposed to fluid with a temperature of 60 °C**
Maximum	2.2 Millijoule: 28.165 8.6 Millijoule: 56.402 19.4 Millijoule: 78.585	47.159	18.210	9.247	239.55
Average	2.2 Millijoule: 98.47 8.6 Millijoule: 562.83 19.4 Millijoule: 109.90	163.15	688.36	94.103	802.33
Minimum	2.2 Millijoule: 587.10 8.6 Millijoule: 856.37 19.4 Millijoule: 8.64	176.12	571.22	565.95	30.112

Impact analysis results

Due to the high importance of ceramic bridges and their fragility, the impact has only been done for ceramic dental bridges. According to the results, the higher the impact energy, the more displacement and stress increase almost linearly. The amount of dynamic stresses in the kinetic energy of 2.2, 8.6, and 19.4 mJ for the impactor is about 1.35, 2.2, and 3 times the static stresses. The concentration of stress is created in the connections, the chewing surface of the tooth, and the connection of the dental bridge to the base teeth. The value of the reaction force fluctuates in nature, and its range and average increase with the increase in kinetic energy. The maximum value of reaction force for kinetic energy 8.6 and 19.4 mJ occurred in 0.04 ms and for kinetic energy 2.2 mJ in 0.02 ms. The changes in the maximum stress in specific time intervals are shown in **Figure 7**.

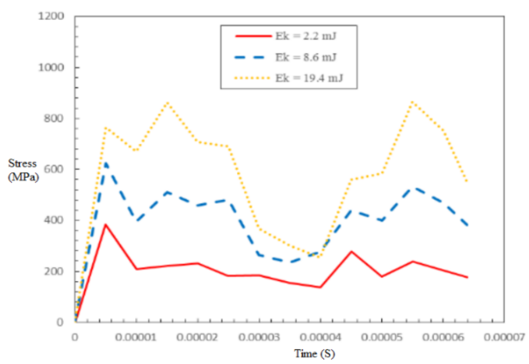


Figure 7. Maximum von Mises stress changes at the kinetic energy of 2.2, 8.6, and 19.4 mJ for the impactor.

As can be seen, irregular fluctuations of force and tension are created after the impact is applied, the range, average, and extreme of which are related to the amount of kinetic energy of the impactor. However, due to the complexity of the geometry, it is not possible to provide an analytical solution and predict the relationship between these fluctuations. In general, these oscillations are a combination of the mode shapes of the investigated set. In addition, due to not considering the damping in the material properties of the model, these oscillations are not damped and the oscillations are stable. These oscillations will be damped if viscoelastic properties are considered for dental components such as pulp.

Table 2 shows the values of the main maximum stresses in the ceramic bridge because of applying an impact load compared to applying a force of 200 Newton's statically, as well as applying a thermal load to use the standard of maximum normal stress. The main stresses in impact loading and cold thermal stimulation exposed to fluid with a temperature of 4 °C are more critical than the rest of the cases. Considering the importance of the impact force and the dynamic examination of the dental bridge, ignoring the dynamic nature of the applied forces leads to the failure of the bridge before the predicted period.

Conclusion

The dental bridge involves a significant part of the tooth and as a result, its mechanical and thermal properties as well as its loading conditions and boundary conditions will have a significant effect on the tension created in the tooth tissue and the dental bridge. According to the results of the distribution pattern of temperature and thermal stress in both type 2 gold and lithium disilicate ceramic dental bridges, 4 seconds after applying the heat flux, it is similar and has reached a stable state. However, the coefficient of thermal expansion of gold is higher than that of ceramic, and as a result, the thermal stress in the tooth tissue and dental bridge in gold restoration is higher than that of ceramic. The maximum value of thermal stress for gold is 1.28 times that of ceramic. Temperature changes in the depth range of the tooth near the nerve, especially in cold stimulation exposed to fluid with a temperature of 4 °C, do not seem favorable. In this study, the presence of cement is ignored. However, for more accurate modeling of temperature distribution, the cement used to attach the bridge to the base teeth and the pulp of the tooth should be modeled as separate structures. The cement used for gold bridges and lithium disilicate ceramic is also different.

The mechanical stress in oblique static loading is 40% higher than in vertical loading, and in both loading modes, the mechanical stress in the lithium disilicate ceramic bridge is slightly higher than that of the gold dental bridge, and no significant difference was observed. However, it is also important to note that in the lithium disilicate ceramic bridge, less tension is created in the tooth tissues, and this is considered a bonus. Because it causes the restorative material in the bridge to fail before the healthy tissues of the tooth, i.e. the remaining crown, which is the base of the bridge and the remaining tissue of the tooth, remains healthy.

The amount of dynamic stresses in the kinetic energy of 2.2, 8.6, and 19.4 mJ for the impactor was about 1.35, 2.2, and 3 times the static stresses. Therefore, ignoring the dynamic nature of applied forces will lead to the failure of the bridge before the predicted period. The maximum mechanical stress was created at the pontic and crown connection points, the crown and base teeth connection points, and on the chewing surface and the lower surface of the artificial tooth. In general, the stresses created in the dental bridge in impact loading and cold thermal stimulation are more critical than other loading modes.

The focus and innovation of this research were on the finite element response of the three-dimensional dental bridge model, and due to the complexity of the model, it is not possible to perform an analytical solution for it. However, the parameters used in the finite element, such as the value of the convective heat transfer coefficient, stiffness, heat conduction coefficient, and specific heat are extracted from laboratory results. For example, in calculating the convective heat transfer coefficient of the fluid, first, the test was performed on a cylindrical sample of copper, whose convective heat transfer coefficient is known, to validate the test method [22]. Of course, testing on a dental bridge will be useful for comparing and validating the finite element results. However, this analysis requires the use of a freshly extracted tooth, placing the temperature sensor in it, and then creating conditions similar to the conditions inside the tooth to perform the test. It is also suggested to continue this work to check the fatigue of dental bridges to estimate the life and the amount of damage. Examining the changes in the geometrical parameters of the dental bridge using the finite element method, similar to what has been done for other dental restorations [31], will be useful for the optimal design of the bridge with the lowest amount of critical stress.

In the simulation section, since the pulp acts as a shock absorber, modeling it separately helps to increase the accuracy of the results. In addition, instead of fixing the root, it is better to model the ligament with springs whose stiffness is different in different directions [10].

Carrying out impact simulation with software such as Ansys Autodyne, which can predict the stress wave and crack initiation and growth, will also be useful in better modeling the impact force, especially the impact caused by the crushing of hard materials between two teeth.

Acknowledgments: None

Conflict of Interest: None

Financial Support: None

Ethics Statement: None

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