Evaluation of Zirconia Paediatric Crowns and Stainless-steel Crowns using Finite Element Stress Analysis

Abstract

Introduction: The aim of this study is to perform Finite Element Stress Analysis (FEA) to determine the stress that stainless-steel and zirconium materials apply to the primary teeth while under occlusal and lateral forces, in order to predict possible situations that may occur in restorative materials and dental tissues as a result of their clinical use.

Objective: The study groups were as follows: stainless-steel crown cemented by glass ionomer cementand dual cure resin cement; zirconium paediatric crown cemented by glass ionomer cement and dual cure resin cement. The control group was the tooth model without decay.

Results: The stresses exerted on the zirconium paediatric crown models were found to be lower than those exerted on the stainless-steel crown models in all cases. The stress values in zirconium paediatric crown models were found to be lower than the values recorded for the healthy tooth model. When the stresses in the pulp were examined, all of the models showed similar results to the stress values recorded for the healthy tooth. The models using dual cure resin cement with both restorative materials showed lower stress values in dentin and pulp than those using glass ionomer cements.

Conclusion: All of the materials included in this study were found to have adequate durability against the maximum bite force and the stress values recorded for the dental tissues were in accordance with the stress values recorded for healthy teeth. Therefore, it was found that the use of zirconium paediatric crowns and resin cement reduces the stress on dental tissues and this is beneficial for the longevity of restorations.

Keywords: Adhesive cement, finite elements analysis, primary teeth, stainless-steel crown and zirconium paediatric crowns.

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Introduction

The primary teeth perform the functions of phonation, aesthetics and space maintenance until the permanent teeth erupt. For this reason, exfoliation of primary teeth is very important in terms of permanent dentition and alveolar development.[1]

Serious material losses can be observed in the crown structures of primary teeth as a result of decay. The treatment of tooth decay should include the removal of the infected tissue and preservation of the remaining tissue, as well as the replacement of any lost crown structure. However, restoration of primary teeth is very difficult in cases of severe decay. Nevertheless, it is important to restore these teeth at least until the time of exfoliation. With full crown restorations of primary teeth that have lost excessive material, this difficulty could be overcome, making the teeth both functionally and aesthetically restorable.[1]

Stainless-steel crowns were first developed for the full crown restoration of primary teeth. The aesthetic acceptability of this material, which is highly durable and easy to apply, is very low. Since several modifications have been developed to eliminate aesthetic insufficiency, stainless-steel crowns have been accepted as the gold standard for the full crown restoration of primary teeth and are frequently being used in clinical practice.[1]

Nowadays, aesthetic restoration of primary teeth is the target, given the increasing expectations and developments in material technology; one of the most up-to-date materials used by paediatric dentists for this purpose is zirconium paediatric crowns.[2] Zirconium paediatric crowns are metal free, but have metal-like mechanical characteristics that can produce natural tooth colour and contour. These crowns are manufactured in different shapes and sizes for primary incisor and molar teeth.[3] Zirconium paediatric crowns are used as an alternative to stainless-steel crowns due to these advantages, but very few studies in literature have shown the success rates of these crowns under occlusal forces.[4]

The finite element analysis (FEA) is a successful method for visualisation and research.[5] In addition, the FEA method can be used to mathematically analyse the changes in the materials caused by various forces.[6]

The aim of this study is to evaluate the stresses exerted by chewing forces on primary teeth that have been restored with stainless-steel or zirconium paediatric crowns by using FEA. In this evaluation, the stresses on the crowns, adhesive cements and dental structures were comparatively analysed. The effects of different adhesive cements (glass ionomer cement and dual cure resin cement) to be used in the cementation of the crowns were also examined. The obtained stress values were evaluated by comparing against the stress values of healthy dental tissues.

Methodology

The study was conducted with five groups :

- Control group: Tooth model without decay defect
- Model 1: Stainless-steel crown model cemented by glass ionomer cement
- Model 2: Stainless-steel crown model cemented by dual cure resin cement
- Model 3: Zirconium paediatric crown model cemented by glass ionomer cement
- Model 4: Zirconium paediatric crown model cemented by dual cure resin cement

In order to compose the models for this study, a maxillary primary second molar tooth model was obtained from a computerised tomography (CT) image. The DICOM format of the CT image was transformed into a 3D model using Mimics (Mimics 15.01, Materialize, Leuven, Belgium) and SolidWorks (SolidWorks 2014 Premium, Concord, Massachusetts). To prepare the working patterns, the necessary amount of substance was removed for the crowns to be applied over the dental tissue in the SolidWorks program. Modelling of crown restorations and adhesive materials was done on the SolidWorks program, taking into account the thicknesses specified in the manufacturer's specifications and defined in the literature. The thickness of the stainless-steel crown was 0.13 mm, the zirconium paediatric crown was 0.73 mm and the adhesive cement was 50 µm (Tables 1 and 2).

Table 1. Number of elements and nodes of the models evaluated in the study[7]

Model	Number of Elements	Number of Nodes
Control Group	514658	724381
Model 1	475565	688826
Model 2	475565	688826
Model 3	521242	744263
Model 4	521242	744263

Table 2. Values of Young's modulus and Poisson's ratio for tooth tissues, crown restorations and adhesive materials[7]

Material	Young's Modulus(E) (GPa)	Poisson's Ratio	References
Enamel	80,35	0,33	8
Dentin	19,89	0,31	8
Pulp	2	0,45	8
Alveolar Bone	11,5	0,3	9
Stainless Steel Crown	200	0,33	10
Zirconium Paediatric Crown	242	0,26	11
Glass Ionomer Cement	10,8	0,3	8
Dual Cure Resin Cement	4,92	0,27	12

Four different forces were applied to the models to simulate maximum bite force and lateral forces. The amount of force was set at 245 N, as specified in the literature.[8] This force was equally distributed over the points, determined by considering the contact relations. The six points selected to imitate maximum bite force was located on the palatal inclination of the mesiobuccal, distobuccal, mesiopalatal and distopalatal tubercles and buccal inclination of the mesiopalatal and distopalatal tubercles (Figure 1).

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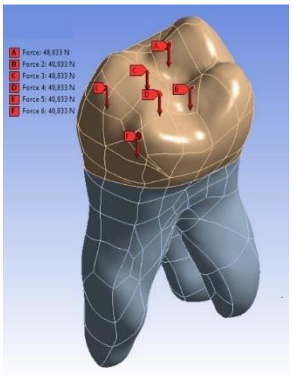
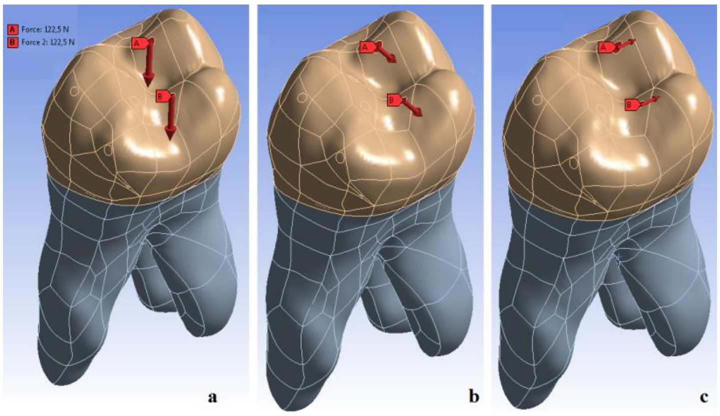
Figure 1. Points selected to imitate the maximum bite force and amount of force.



The two points selected to imitate the lateral forces were located on the palatal inclination of mesiobuccal and distobuccal tubercles. The maximum bite force was applied parallel to the long axis of the tooth, while the lateral forces were applied at three different angles (0°, 45° and 90°) (Figure 2).

Figure 2. Points selected to imitate the lateral force (a. 0°, b. 45° and c. 90°) and amount of force.



The stresses caused by the forces applied via the Ansys Workbench 14.0 (Ansys Inc., Canonsburg, Pa., USA) program were examined as Von Mises stress values.

Results

The stress distribution was displayed in decreasing order, from red to dark blue with colour scales on the models. In addition, the maximum Von Mises stress values for

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all structures and tissues against axial and lateral forces (at angles of 0°, 45°, and 90°) are reported in Table 3.

Table 3. Maximum Von Mises stress values (MPa) of all structures and tissues against axial and lateral (with 0°, 45° and 90° angle) forces.

	Enamel		Dentin	Pulp
Tooth without defect	Axial:439,59		Axial:21,955	Axial:1,0926
	0^0:857,54		0^0:42,883	0^0:1,6455
	45^0:622,15		45^0:44,863	45^0:1,959
	90^0:1205,4		90^0:31,823	90^0:2,6929
	Crown Restoration	**Luting Cement**	**Dentin**	**Pulp**
SSC+GIC	Axial:550,58	Axial:72,375	Axial:43,97	Axial:1,0611
	0^0:1190,01	0^0:216,3	0^0:130,34	0^0:1,5978
	45^0:1156,9	45^0:237,06	45^0:123,9	45^0:1,9224
	90^0:1487,5	90^0:124,79	90^0:79,562	90^0:2,7029
SSC+Resin	Axial:572,66	Axial:58,157	Axial:38,161	Axial:1,0611
	0^0:1305,7	0^0:173,92	0^0:111,76	0^0:1,6104
	45^0:1326,3	45^0:188,67	45^0:104,95	45^0:1,9296
	90^0:1584,2	90^0:96,568	90^0:66,696	90^0:2,7322
Zirconium+GIC	Axial:435,29	Axial:13,886	Axial:11,037	Axial:1,0859
	0^0:806,44	0^0:39,094	0^0:28,815	0^0:1,3373
	45^0:696,26	45^0:39,925	45^0:29,349	45^0:1,9042
	90^0:1196,7	90^0:23,558	90^0:19,032	90^0:2,5861
Zirconium+Resin	Axial:435,92	Axial:10,719	Axial:9,3309	Axial:1,086
	0^0:809,6	0^0:29,073	0^0:22,819	0^0:1,3385
	45^0:706,55	45^0:29,461	45^0:22,88	45^0:1,9179
	90^0:1197,7	90^0:16,833	90^0:15,145	90^0:2,6063

SSC: Stainless steel crown Zirconium: Zirconium paediatric crown GIC: Glass ionomer cement Resin: Dual cure resin cement

The stresses were visualised in colour coding, ranging from dark blue (minimum stress) to red (maximum stress) on Figures 3, 4, 5 and 6.

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Figure 3. Stress patterns and maximum Von Mises stress values (MPa) of all structures and tissues under the axial forces.

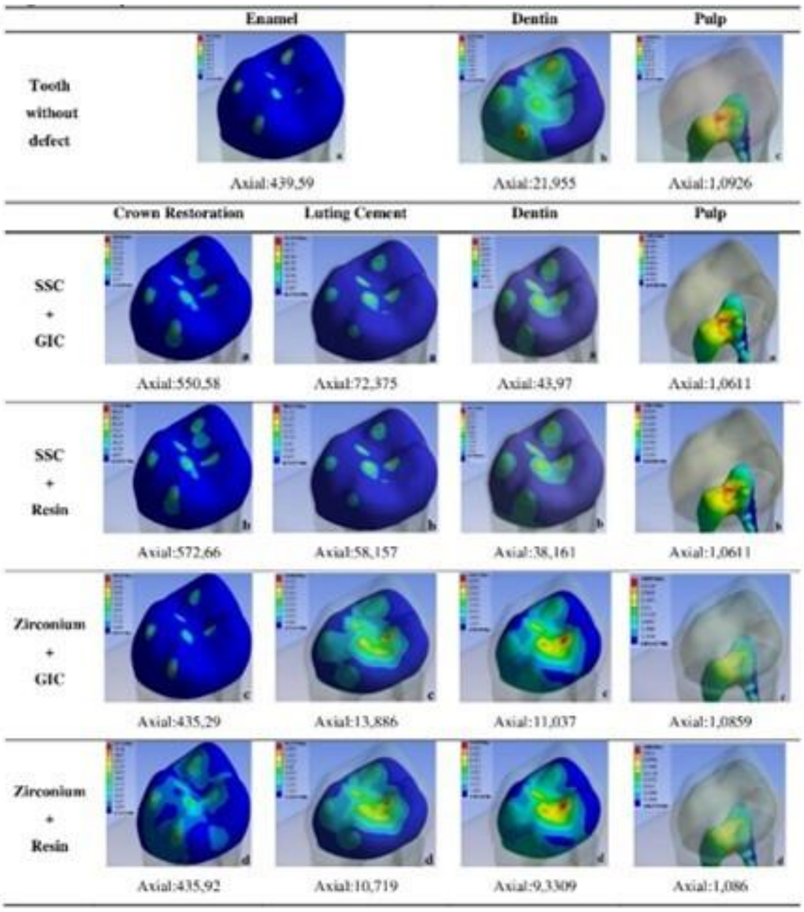

Figure 4. Stress patterns and maximum Von Mises stress values (MPa) of all structures and tissues under the 0° angle lateral forces.

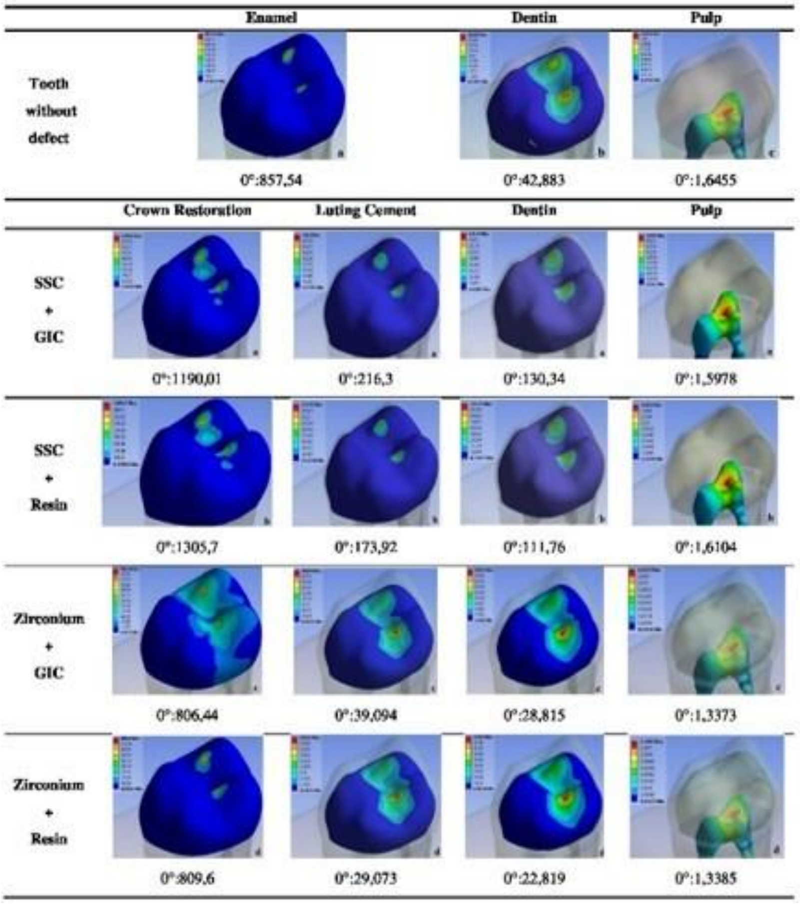

Figure 5. Stress patterns and maximum Von Mises stress values (MPa) of all structures and tissues under the 45° angle lateral forces.

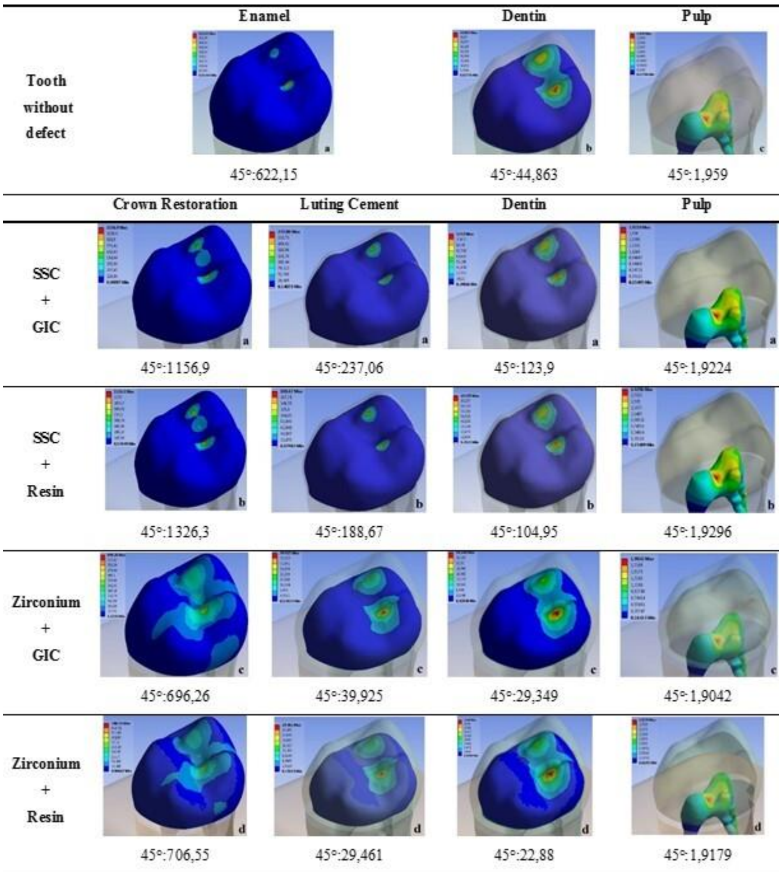

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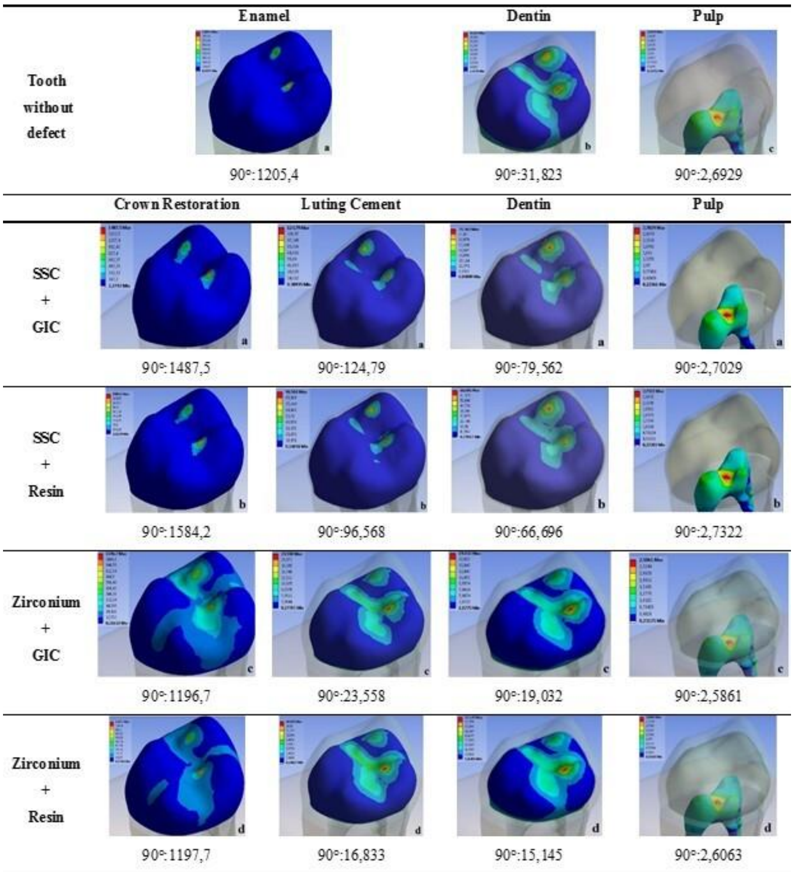
Figure 6. Stress patterns and maximum Von Mises stress values (MPa) of all structures and tissues under the 90° angle lateral forces.



High-stress fields were usually identified at the points where the forces were applied. The stresses identified were found to be lower than the stresses that the materials could tolerate. Lateral forces caused higher stress on the crown restorations. The stresses exerted on the zirconium paediatric crown models were significantly lower than those exerted on the stainless-steel crown models in all cases. Although no significant differences were observed due to the adhesive cements, the results showed that the models using dual cure resin cement had slightly lower stress values than those using the glass ionomer cement under the same conditions.

Discussion

The treatment of tooth decay includes the removal of the infected tissue, preservation of remaining tissue and replacement of the lost crown structure. However, it is very difficult to carry out restoration when the primary teeth are severely decayed. Regarding full crown restoration of primary teeth with excessive loss of material, this difficulty could be overcome to a certain extent and the functionality and aesthetics could be restored.[1]

Failure to restore primary teeth with severe tissue loss led researchers to develop new crowns. For this purpose, crowns with aesthetic features for primary incisors and crowns with high mechanical strength and aesthetic features for primary molars were developed.[9] Zirconium paediatric crowns are biocompatible materials have been used in paediatric dentistry since 2010; they are both aesthetically pleasing and durable against the forces they are exposed to in the posterior region of the mouth.[10]

Long-term clinical follow up is not yet available in the literature on this novel material. In this study, zirconium paediatric crowns meeting current aesthetic expectations, showing resistance against chewing forces and developed alternatively with stainless-steel crowns, which have advantages such as strength, ease of use, and cost, were examined by FEA. As a control group, a healthy primary tooth crown without any crown restoration or loss of material due to cavities or trauma was selected. The stress values observed in the dental tissues in both models were compared by FEA.

FEA allows for evaluation of the stresses on a structure while it is under force.[11] For the application of FEA, mathematical models are generated and the stresses are applied to these models. This method is known to yield consistent results that are in conformity with the results of other studies. In addition, with the FEA method, the intensity and direction of applied forces can be easily changed and the analysis can be easily repeated. The results can be obtained faster with FEA than with other experimental methods.[12]

The use of 3D models during analysis is important in terms of reflecting the volume, irregularities and changes in different layers of an object. In a study comparing the reliabilities of 2D and 3D FEA methods, it was concluded that 3D analysis results are better in determining stress distributions. This observed difference can be attributed to the fact that complex structures work more realistically with 3D models than with 2D models.[13]

It is not possible for biological structures to be homogeneous and isotropic. However, in the case of FEA, despite using structures that are homogeneous and isotropic and performing the analysis using mean values, the results closely reflect reality.[14] In many studies comparing the stress values, the objects were assumed to be homogeneous and isotropic and this did not affect the results.[15]

While using FEA, the near-reality modelling of the tissues ensures that the results are closest to reality. In studies involving multi-layered living tissues, it is necessary to reflect the inner structures of the tissues via the models. Utilising CT images for modelling tissues such as bone and teeth allow each layer to be modelled separately for use in FEA. In many studies performed on dental structures, DICOM format CT images were used to obtain 3D models.[13,16]

DICOM formatted data must be transferred to medical image control systems in order to be modelled and analysed in 3D. Through medical image control systems, DICOM formatted data is converted to point cloud images. The Mimics program is frequently used for this transformation in many studies in medicine and dentistry, especially when making various adjustments to the models. The Mimics program allows the precise creation of all 3D models by using image data, enabling the processing and correction of the models. It allows the generated 3D data to be converted into many output formats suitable for use in different engineering applications.[13]

Transforming point cloud images obtained with the Mimics program into solid models and correcting the mistakes on the models makes it possible to obtain results that are closer to reality. For this purpose, a computer-aided 3D design and production program should be utilised. Through such programs, it is also possible to create models of different structures required for the study. The SolidWorks program can be used to transform point cloud images into solid models and model structures.[13] In a study comparing Geomagic and SolidWorks, it was reported that the results produced by the combination of SolidWorks and Mimics were closer to reality than those produced by the Geomagic program.[17]

With the Mimics program, hard and soft tissues are modelled with the appropriate Hounsfield (HU) values during the creation of 3D images. HU units are defined as linear transformations of a measured x-ray absorptivity of a material relative to water. The HU value for water is assumed to be 0 and for air, -1000. In light of these two constants, other tissues take different values.[18]

Algor, Abaqus, Ansys, Comsol, Cosmos, I-Deas and Marc are the most frequently used software programs in dentistry literature and the software programs used for FEA have many technical differences.[13] In FEA studies, Ansys is the most frequently used software program, which is why it was used in this study.

For the paediatric patient group, studies have reported a mean molar bite strength of 213.17 N in the dentition period and 333 N in the early, mixed-dentition period.[19] In a different study, the mean bite force was reported to be 196 N in children aged 3–5 years and 296 N in children aged 6–8 years.[20] In FEA studies examining full crown restorations applied to the primary teeth, a force of 245 N was applied to the second molar tooth model to imitate the bite force.[8,16] In light of this data, the maximum bite force value for the dentition period was set as 245 N in order to assess the durability of the materials against the maximum conditions in the mouth. In addition, the crowns were modelled on the second molar tooth, as it is exposed to greater occlusal forces. While axial forces were applied parallel to the long axis of the tooth, lateral forces were applied at three different angles.

The teeth meet the force they are exposed to when closing due to occlusal relationships with the opposing teeth, dividing the force they are subjected to during closing from the points where there is tubercle contact, not at a single point.[8,21] In this study, four different forces were applied in different directions to simulate the maximum bite force and lateral forces. The amount of force was determined to be 245 N in light of the literature knowledge. This force is evenly distributed to the points of application. Six points on the upper second molar tooth (mesiobuccal tubercle palatal inclination, distobuccal tubercle palatal inclination, mesiopalatal tubercle buccal inclination, distopalatal tubercle buccal inclination, mesiopalatal tubercle palatal inclination and distopalatal tubercle palatal inclination) were selected to imitate the maximum bite force and two points (mesiobuccal and distobuccal tubercle palatal inclination) were selected to simulate lateral forces. The forces were applied on the circular areas with a radius of 0.5 mm.

When stress values in FEA studies are examined, the separate evaluation of normal stress and shear stress may cause erroneous interpretations; therefore, the components of all existing stresses should be taken into consideration during analysis. Von Mises stress value, which allows for the inclusion of normal stress and shear stress with significant numerical results, provides data suitable for evaluation in FEA. This value is accepted as an appropriate parameter for determining the stresses occurring as a result of brittle materials under force.[22]

In studies where the stresses against forces were investigated by FEA, it was found that the stresses on the external surfaces of the objects were concentrated on the application points of the forces and their neighbouring regions, which was an expected situation. However, the stresses in the deeper parts of the object were affected by the modulus of elasticity of the material. The stress that is generated because of this is distributed in these layers in different ways.[15]

The high elasticity modulus of a material causes stress to increase in the material. Accordingly, the stress transmitted to the underlying layers is reduced. This only happens when a restored tooth is evaluated and the elasticity modulus of the restorative material is high. Then the stress transmitted to the dental tissues will decrease.[23] In this study, the elasticity modulus of zirconium was higher than that of stainless steel. As a result, when stresses transmitted to adhesive cements, dentin and pulp were compared, the stress values reported for zirconium paediatric crown models were lower than those reported for stainless-steel crown models. Also, when the adhesive cements were examined, the glass ionomer cements with higher modulus of elasticity than the dual cure resin cements absorbed more stresses in their structures and less stress was transmitted to the lower layers than in the case of dual cure resin cements.

Conclusion

In this study, FEA was performed on the models of primary teeth with full crown restorative materials and adhesive cements, obtained by means of computer programs. By comparatively evaluating the obtained data, we aimed to determine the

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appropriateness of the clinical use of these materials in dental restorations for paediatric patients. Furthermore, the resulting stresses on the dental structures were evaluated to contribute to the literature. However, in order to obtain definite conclusions about the clinical success of these materials, long-term in vivo follow-up studies and different in vitro stress analysis techniques and studies comparing FEA results are required.

REFERENCES

1. Waggoner WF. Restorative Dentistry for the Primary Dentition. In: Pediatric Dentistry: Infancy Through Adolescence. Eds: Pinkham JR, Casamassimo PS, Fields Jr HW, McTigue DJ, Nowak AJ. St. Louis: Saunders, 2005;341-374.

2. Fellagh HF. Evaluation of full coronal esthetic restorations in primary incisors: clinical success, Parental satisfaction, In-vitro fracture resistance and Bacterial adhesion. Yeditepe University, Institute of Health Sciences, Department of PediatricDentistry. Istanbul, 201;1-224.

3. Karaca B, Ozbay G, Kargul B. Primary zirconia crown restorations for children with early childhood caries. Acta Stomatol Croat 2013;47(1):64-71.

4. Innes NP, Ricketts DN, Evans DJ. Preformed metal crowns for decayed primary molar teeth. Cochrane Database Syst Rev 2007;(1):CD005512.

5. Schmid, Alois, Thomas Strasser, and Martin Rosentritt. "Finite element analysis of occlusal interferences in dental prosthetics caused by occlusal adjustment." The International Journal of Prosthodontics. 2021.

6. Srirekha A, Bashetty K. Infinite to finite: an overview of finite element analysis. Indian journal of dental research: official publication of Indian Society for Dental Research 2010;21(3):425-432.

7. Christensen GJ. Clinicians Report – Pediatric Crowns are Growing Up. Vol. 5. Addendum: CR publications; 2012.

8. Prabhakar AR, Yavagal CM, Chakraborty A, Sugandhan S. Finite element stress analysis of stainless steel crowns 2015;33:183-191.

9. Qureshi, Mohd Tanzeem, et al. "Crowns in Paediatric Dentistry–A Review." Annals of the Romanian Society for Cell Biology. 2021; 16040-16045.

10. Denry I, Holloway JA. Ceramics for dental applications: a review. J Dent Mater 2010;3:351-368.

11. Sannino G, Pozzi A, Schiavetti R, Barlattani A. Stress distribution on a three-unit implant-supported zirconia framework. A 3D finite element analysis and fatigue test. Oral Implantol 2012;5:11-20.

12. Deolikar, Sayali, Nilesh Rathi, and Vini Mehta. "Comparative evaluation of stress generation in primary teeth restored with zirconia and BioFlx crowns: A finite element analysis." Majalah Kedokteran Gigi 57.2 (2024): 80-86.

13. Bulaqi HA, Mashhadi MM, Samandari HS, Geramipanah F. Effect of increased crown height on stress distribution in short dental implant components and their surrounding bone: A finite element analysis. J Prosthet Dent 2015; 113(6):548-557.
14. Alvarez-Arenal A, Segura-Mori L, Gonzalez-Gonzalez I, Gago A. Stress distribution in the abutment and retention screw of a single implant supporting a prosthesis with platform switching. Int J Oral Maxillofac Implants 2013;28:112-121.
15. Asmussen E, Peutzfeldt A. Class I and Class II restorations of resin composite: a FE analysis of the influence of modulus of elasticity on stresses generated by occlusal loading. Dent Mater 2008;24:600-605.
16. Prabhakar AR, Chakraborty A, Nadig B, Yavagal C. Finite element stress analysis of restored primary teeth: A comparative evaluation between stainless steel crowns and preformed zirconia crowns. Int J Oral Health Sci 2017;7:10-5.
17. Afsar, Emrah, et al. "Use of the finite element analysis to determine stresses in the knee joints of osteoarthritis patients with different Q angles." Journal of the Brazilian Society of Mechanical Sciences and Engineering 2017; 1061-1067.
18. Pauwels R, Jacobs R, Singer SR, Mupparapu M. CBCT-based bone quality assessment: are Hounsfield units applicable? Dentomaxillofac Radiol 2015;44:20140238.
19. Castelo PM, Pereira LJ, Bonjardim LR, Gavião MB. Changes in bite force, masticatory muscle thickness, and facial morphology between primary and mixed dentition in preschool children with normal occlusion. Ann Anat 2010;192(1):23-26.
20. Kamegai T, Tatsuki T, Nagano H, Mitsuhashi H, Kumeta J, Tatsuki Y, Inaba D. A determinant ion of bite force in northern Japanese children. Eur J Orthod 2005;27:53-57.
21. D’souza, Kathleen Manuela, and MeenaAjay Aras. "Three-dimensional finite element analysis of the stress distribution pattern in a mandibular firstmolar tooth restored with five different restorative materials." *TheJ ournal of the Indian Prosthodontic Society* 2017;53.
22. Yaman SD, Karacaer O, Sahin M. Stress distribution of post-core applications in maxillary central incisors. J Biomater Appl 2004;18:163-177.

23. He, J.,Zheng, Z., Wu, M., Zheng, C., Zeng, Y., & Yan, W. Influence of restorative material and cement on the stress distribution of endocrowns: 3D finite element analysis. *BMC Oral Health*, 2021; *21*(1), 1-9.