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ORIGINAL RESEARCH

Evaluation of stress generation in core build up-material of mutilated primary teeth: a comparative finite element analysis between BioFlx, stainless steel and zirconia crowns

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Abstract

Stainless-steel crowns (SSCs) are the most durable restorative option for deciduous teeth, although they are unsightly. However, prefabricated zirconia crowns (ZCs) look more pleasant but require substantial dental preparation. Recently, BioFlx crowns have been introduced as a white-colored alternative to SSCs, providing both flexibility and aesthetics. However, clinical trials have not assessed their oral cavity load-bearing capacity and suitability for repairing severely decayed deciduous teeth. To address this gap, the present study compared the shear stresses generated by BioFlx crowns, ZCs and the gold standard SSCs when restoring extensively decayed deciduous teeth using finite element analysis (FEA). The restoration was represented by three finite element models with the identical tooth structure: BioFlx, SSC and ZC, constructed using a Trios 3 scanner and exported for analysis using ANSYS. The FEA results showed that ZCs had the maximum axial static load stress at 40.91 MPa, followed by SSCs at 39.331 MPa and BioFlx at 14.009 MPa. ZCs produced 2.932 MPa at 45°, SSCs 3.005 MPa and BioFlx 0.3227 MPa. ZCs had a maximum primary stress of 3.055 MPa at 0°, while SSCs and BioFlx had 2.3 and 0.3017 MPa, respectively. Deformation analysis revealed that under a load direction of 90°, SSCs deformed by 5.978 mm, ZCs by 5.971 mm and BioFlx by 5.971 mm. When the load was applied at an angle of 45°, SSCs deformed by 6.527 mm, ZCs by 5.444 mm and BioFlx by 5.447 mm. SSCs deformed 5.452 mm at 0° load, while ZCs and BioFlx deformed 6.472 and 6.479 mm, respectively. Based on these findings, BioFlx crowns, in combination with the underlying core material, can withstand maximum loads, suggesting that a mutilated primary posterior tooth restored with glass ionomer cement and a BioFlx crown may be a viable option for frequent clinical use.

Keywords

Deciduous maxillary second molar; Finite element analysis; Fracture resistance; BioFlx crown; Preformed zirconia crown; Stainless steel crowns

1. Introduction

The prevalence of dental caries and the resulting destruction of primary teeth structure is observed in 70% of children. In clinical practice, decaying teeth are often salvaged through restoration or pulp therapy, which can weaken the tooth due to loss of tooth structure [1, 2]. The teeth play a crucial role during biting and chewing, generating biomechanical forces during mastication [1–4], which are transmitted through various tooth tissues, including the enamel, dentin, pulp, cementum and periapical tissues. However, the dissipation pattern of stresses in endodontically treated teeth differs from that of untreated teeth [3, 4]. In cases where teeth are severely damaged, there is an increased risk of fracture, necessitating the use of a specific material for restoring primary teeth [1–4]. endodontically treated teeth have limited tooth structure available to support a definitive prosthesis. Therefore, restorative materials such as amalgam, glass ionomer cement (GIC), resin-modified glass ionomer cement, and resin composites are used to compensate for the lack of tooth structure and enhance crown retention and reinforcement of coronal structures [5]. Among these materials, GIC is the most commonly used post-obturation restorative material in primary teeth. It acts as a self-adhesive material that does not require conditioning, thus avoiding the compromise of the coronal seal in endodontically treated teeth [6], and has an elastic modulus of GIC Type I of 10.8 GPa and a Poisson ratio of 0.3.

The use of full-coverage restorations like prefabricated stainless-steel crowns (SSCs) and zirconia crowns (ZCs) has been suggested for the treatment of posterior teeth with extensive tooth loss [7]. Guidelines for pediatric restorative dentistry recommend SSCs when extensive tooth decay affects at least two surfaces [8]. SSCs have an elastic modulus of 200 GPa and a Poisson's ratio of 0.33. They are considered safe and clinically effective, but parents often dislike their appearance due to their low aesthetic appeal [9]. In recent years, manufacturers have introduced preformed ZCs as an alternative, which offer superior biocompatibility, aesthetics and mechanical strength [10]. However, zirconia requires extensive crown preparation for a precise fit and it is a costly option. Zirconia crowns have mechanical properties such as flexural strength >1000 MPa, elastic modulus of 210 GPa and hardness of 10 Gpa, which exceed those of human enamel (with flexural strength, 280 Gpa; elastic modulus, 94 Gpa; hardness, 3.2 GPa), and a Poisson's ratio of 0.28. To address the concerns regarding aesthetics and excessive tooth preparation, a white and flexible hybrid resin polymer crown called BioFlx has been introduced. BioFlx aims to combine the advantages of both SSCs and ZCs by offering conservative preparation similar to SSCs while providing aesthetic qualities comparable to ZCs, as they are tooth-colored.

The recent introduction of BioFlx crowns brings a new option to the market. These crowns are preformed, resin-based, flexible and tooth-colored, available in a single shade. The physical properties of the resin used in BioFlx crowns differ from those of stainless steel and zirconia materials. It is important to note that the response of resin, stainless steel and zirconia to masticatory stresses can vary in intraoral conditions. BioFlx crowns are specifically designed to adapt to occlusal forces, exhibiting good abrasion resistance and load-bearing capacity. They can be adjusted and trimmed to achieve proper fit on the tooth being crowned. However, it is worth mentioning that resin has a lower modulus of elasticity than the other materials, resulting in different stresses in the tooth or the core build-up material used for rehabilitation. The clinical performance of a crown relies on several factors, including the amount of stress generated in the crown, the transmission of stress in the core material, and the strength of the core material itself. Therefore, this study aims to investigate the differences in the performance of BioFlx crowns compared to SSCs and ZCs regarding their ability to withstand occlusal stresses.

Due to the complex and dynamic nature of intraoral environments, research on this topic is limited. Therefore, biomechanical studies involving various dental procedures such as restorative, prosthetic, root canal, orthodontic and implant treatments are often conducted *in vitro*. A finite element model (FEM) can be generated to simulate the intraoral environment. When a load is applied to a structure, it undergoes deformations and experiences stress. However, structural failure may occur if these stresses exceed the elastic limit and become extreme [11]. Currently, there is a lack of research investigating the reaction of glass ionomer cement (GIC) as a core build-up material combined with stainless steel, zirconia and Bioflx resin under masticatory loads. This study aims to provide valuable clinical guidance for retaining mutilated teeth and making informed decisions regarding crown and core build-up materials. Specifically, through the use of finite element analysis (FEA), this study aims to observe and compare the shear stresses generated in the crown and post-endodontic restoration when rehabilitated with BioFlx crowns, SSCs and ZCs.

2. Materials and methods

This study selected three primary maxillary second molars free from caries as samples. Before the experiment, the extracted teeth were cleaned using 3% sodium hypochlorite and ultrasonic scaling. The occlusal portion of the teeth was then reduced to a height of 3 mm above the cementoenamel junction (CEJ). To replicate a mutilated primary tooth, most of the enamel and dentin were removed. Following the tooth preparation, post-endodontic restoration was performed using restorative glass ionomer cement (Type IX). A single operator performed the crown preparation on models to eliminate inter-operator bias. The crowns were prepared following the guidelines of stainless-steel Crown (3M ESPE), Zirconia (Kids-E-Dental) and Bioflx (Kids-e-Dental).

2.1 Creation of finite element models

The Trios 3shape intraoral scanner was used to capture three-dimensional images of the prepared primary second molars and saved in STL format. Then, the model was divided into tetrahedral portions and transformed into cloud data points using the ANSYS software (version 12; ANSYS Inc; Canonsburg, PA, USA), followed by creating surface models for each primary tooth. Upon importing the models into the software, the Poisson's ratio and modulus of elasticity values corresponding to the materials were assigned to the respective models. The specific values for each material are shown in Table 1.

TABLE 1. Elastic modulus and Poisson's ratio of materials used in the model.

Material	Elastic Modulus (Gpa)	Poisson's Ration
Enamel	80.350	0.33
Dentin	19.890	0.31
Periodontal ligament	0.069	0.45
Cancellous bone	0.490	0.30
Cortical bone	14.700	0.30
GIC Type II cement	12	0.30
GIC Type I cement	10.800	0.30
Stainless-steel crown	200	0.33
Bioflx crown	5.030	0.39
Kids-e-zirconia crown	250	0.28

GIC: glass ionomer cement.

The trios 3 scanner was used to generate the digital model of the stainless steel, zirconia and BioFlx crowns selected for the study (Fig. 1).

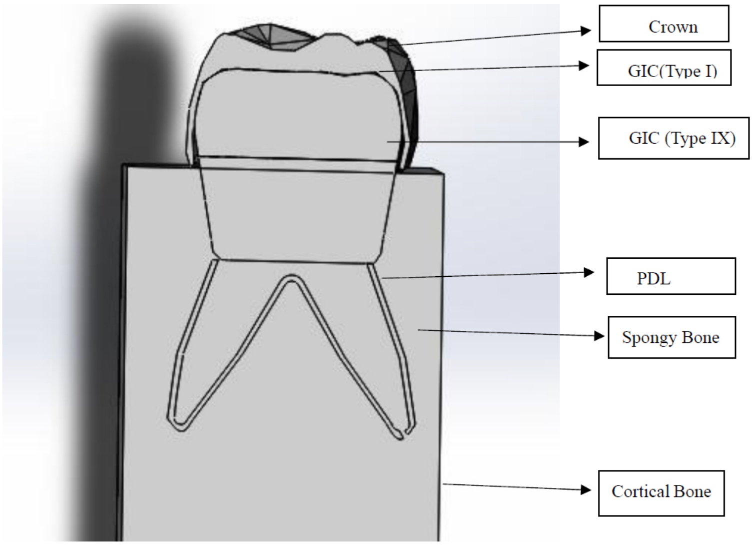

FIGURE 1. Schematic representation of Crown, GIC and dentine. GIC: Glass ionomer cement; PDL: Periodontal ligament.

2.2 Load Application

After the scans, the prepared teeth were fitted with SSCs, ZCs and BioFlx crowns, respectively. To simulate the space required for luting cement (GIC type I), a 100-micron gap was created on the model by merging the scanned images of the tooth with the crowns. To replicate the physiological masticatory pressures experienced by children in the corresponding age group, a total of 245 N of vertical and angular static stresses were applied to the tooth crowns [3, 5]. Specifically, axial forces were applied to the internal slopes of the buccal cusps, internal slopes of the palatal cusps and exterior slopes of the palatal cusps [3]. Additionally, angled forces at 0, 45 and 90 degrees were applied to the palatal slopes of the buccal cusps to replicate lateral chewing forces. The stress values and patterns resulting from the applied loads were computed using the von Mises measurement criteria.

The following equation was used:

$$\sigma e = 1/2([\sigma 1 - \sigma 2]\,2 + [\sigma 2 - \sigma 3]\,2 + [\sigma 3 - \sigma 1]2)1/2$$

Where, $\sigma 1$, $\sigma 2$ and $\sigma 3$ represent the principal stresses within the material [9].

3. Results

Based on the Von Mises measurement criteria and FEA, the stress and deformation values generated in the three different crown materials (stainless steel, zirconia and BioFlx) are as follows:

Under axial static load, the stress values were 2.164 GPa for zirconia, 3.062 GPa for stainless steel and 0.3850 GPa for BioFlx. Zirconia generated the highest stress, while BioFlx had the lowest stress among the three materials. Under lateral static load, the forces were applied in two different directions: 45° and 0°. When subjected to lateral static load at 45°, Zirconia had a maximum principal stress of 2.932 GPa, while stainless steel and BioFlx had stresses of 3.005 MPa and 0.3227 GPa, respectively. At 0°, Zirconia generated a maximum principal stress of 3.055 GPa, while stainless steel had a stress of 2.3 Pa, and BioFlx had a stress of 0.302 GPa (**Supplementary Fig. 1**).

Table 2 presents the results obtained from the FEA regarding the deformation of the three different crown materials (stainless steel, zirconia and BioFlx) under various load conditions. Under a load direction of 90°, stainless steel exhibited a deformation of 5.978 mm $\times$ 10^6, zirconia deformed by 5.971 mm $\times$ 10^6, and BioFlx deformed by 5.971 mm $\times$ 10^6. When subjected to a load direction of 45°, stainless steel deformed by 6.527 mm $\times$ 10^6, zirconia by 5.444 mm $\times$ 10^6, and BioFlx by 5.447 mm $\times$ 10^6. Furthermore, under a load direction of 0°, stainless steel showed a deformation of 5.452 mm $\times$ 10^6, while zirconia and BioFlx exhibited deformations of 6.478 mm $\times$ 10^6 and 6.479 mm $\times$ 10^6, respectively. Notably, BioFlx demonstrated higher deformation values than stainless steel and zirconia in these load conditions (**Supplementary Fig. 2**).

4. Discussion

Pediatric crowns must be adjustable and possess a retention rate that can sustain masticatory forces, and the crown materials should cause no or minimal destruction to the opposing teeth and maintain an appropriate oral hygienic environment for healthy surrounding tissues [12]. BioFlx is a recently introduced prefabricated crown made from a proprietary tooth-colored hybrid resin polymer. It stands out due to its unique combination of characteristics, offering both the elasticity and flexibility typically associated with stainless-steel crowns and the aesthetic appeal comparable to zirconia crowns. Given these distinctive features, it is essential to investigate the clinical utility of this polymeric material, as it represents a notable alternative for improving pediatric treatment.

Prabhakar *et al*. [5] investigated the effectiveness of SSC in withstanding masticatory forces and reported that severely damaged teeth with up to 75% tooth loss were able to withstand prosthesis failure when restored with SSC. Another study by Prabhakar *et al*. [5] evaluated long-term restorative therapy using ZCs and SSCs of severely damaged posterior primary teeth.

TABLE 2. Stress generation and deformation in different crown materials under axial and lateral static load using FEA.

Load	Zirconia		BioFlx		Stainless steel	
	Stress (Gpa)	Deformation (mm × 10^6)	Stress (Gpa)	Deformation (mm × 10^6)	Stress (Gpa)	Deformation (mm × 10^6)
90°	2.164	5.971	0.3850	5.971	3.062	5.978
45°	2.932	5.444	0.3227	5.447	3.005	6.527
0°	3.055	6.478	0.3017	6.479	2.300	5.452

The findings indicated that ZCs performed better for teeth with less than two-thirds of the original tooth structure than SSCs, which could be attributed to the reduced stress build-up in ZCs [10]. It is important to note that ZCs require extensive tooth preparation and can cause wear on natural opposing teeth [13]. On the other hand, SSCs demonstrated greater marginal adaptation and reduced wear on the opposing tooth. However, despite these advantages, both parents and patients preferred ZCs over SSCs due to their superior aesthetics [14].

It is essential to investigate the aesthetics and biomechanical behavior of prefabricated crowns made from various materials when placed on severely damaged primary teeth. When a structure is subjected to a load, it experiences stress that can result in deformation. Analyzing the stress distribution on a tooth model can be achieved through FEA, which allows the examination of complex structures [10]. The construction of the model used in FEA is closely intertwined with its ability to simulate a dental prosthesis with regions of higher tensile stress being more prone to fracture. Therefore, it is crucial to study these high-stress areas and identify the factors that contribute to peak tensile stresses. A previous study indicated that primary teeth can withstand bite forces ranging from 163 to 330 N [15]. Based on these reports, this present study applied a mean force of 245 N on the cuspal planes, consistent with the work conducted by Prabhakar *et al*. [10]. Maxillary second primary molars were specifically chosen for this study due to their crucial role in maintaining arch length and preventing mesiopalatal rotation of the permanent first molar [11]. Overall, our study sheds light on the stress distribution within the tooth model and provides insights that might help predict the likelihood of fracture in regions experiencing high tensile stress.

The present study revealed that BioFlx crowns could withstand masticatory stresses in severely damaged teeth restored with a GIC core compared to zirconia and SS crowns under simulated conditions. When the GIC core was restored using BioFlx crowns, minimal stress generation was observed. This finding contrasts with the study conducted by Prabhakar *et al*. [10], which suggested that ZCs were more suitable for teeth with less than two-thirds of their original tooth structure. The difference in outcomes can be explained by the fact that BioFlx crowns, composed of a hybrid resin polymer, have a lower modulus of elasticity than zirconia. Additionally, when compared to resin-based core materials, GIC is more likely to fail under masticatory loads when used with a rigid crown material. In contrast, the flexibility of BioFlx may reduce stress on the GIC core material, thus promoting its longevity.

Human dentin shares similarities with filled polymers used in dental restorations [16]. Both dentin and filled polymers consist of a matrix substance and filler particles [17]. The mechanical properties of these materials are influenced by the composition and distribution of these constituents [18]. For instance, the type, size and distribution of filler particles within the matrix can affect the hardness and elastic modulus of both dentin and filled polymers [19]. Additionally, their behavior under load, including deformation and elastic recovery, can be comparable. Materials such as rubber, polymers, elastomers and certain fiber-reinforced composites, which exhibit low modulus of elasticity and high tensile strength, share mechanical qualities with both dentin and filled polymers [20, 21]. Such materials are preferred in periodontal therapy, orthodontic applications and other dental procedures due to their ability to withstand masticatory forces and adapt to the tooth's shape [22]. Furthermore, their low modulus of elasticity can help reduce the likelihood of tooth and core structure failure [23]. In a study by Prabhakar *et al*. [10], the stress generated in teeth restored with zirconia crowns was compared to those restored with metal crowns. The findings demonstrated that teeth restored with zirconia crowns exhibited lower stress generation than those restored with metal crowns. This difference was attributed to the higher elastic modulus of zirconia, which enabled more uniform load distribution and reduced the likelihood of localized stress concentrations [10].

Our study revealed that ZCs exhibited the highest stress levels, followed by SSC and BioFlx crowns under both axial and lateral static loads, suggesting that stainless steel and zirconia crown materials may be more susceptible to failure under lateral loads compared to the BioFlx crown material. Therefore, BioFlx may have lower resistance to stress but higher deformation behavior compared to the other two materials. Based on these results, zirconia appears to be the stiffest material, followed by stainless steel, while BioFlx appears to be the most flexible and least brittle material. The flexibility and pliability of Bioflx crowns allow them to deform under pressure and distribute forces over a wider surface area, reducing overall stress on the crown. Furthermore, the Bioflx crown's increased adaptation and fit contribute to reduced stress on the GIC core and tooth structure. This can be attributed to its lower elastic modulus than ZCs and SSCs. Interestingly, the cervical region was found to produce the highest stress in all groups.

Chung SY *et al*. [24] investigated the stress generation in teeth with zirconia crowns across different groups and sites and reported that the stress generated in teeth with ZCs varied depending on the tooth type and its position in the mouth. Specifically, the molars exhibited the highest stress levels, followed by the premolars and incisors. Among the molars, the first molars displayed higher stress than the second molars. These variations in stress levels can be attributed to differences in tooth anatomy and loading conditions [24].

The materials utilized in dental crowns possess inherent deformability when subjected to differential loading during the dynamic movement of the mandible during mastication, which plays a crucial role in the functional performance of dental crowns. A higher deformation value indicates that the material is less resistant to stress, potentially leading to crown collapse or changes in shape. Such deformations can have implications for crown fit and its ability to fulfill its intended purposes, including tooth protection, occlusion restoration and aesthetics maintenance [16, 22].

The levels of deformation can vary depending on the specific approaches and procedures used, as well as unique variations in tooth structure and composition. The acceptable degree of deformation will also vary depending on the dental prosthesis's specific requirements and the patient's needs. Our study focused on assessing moderate masticatory loads commonly experienced by the pediatric population. When the deformation value is higher, the material is more flexible but less stress-resistant and can potentially lead to crown fractures or changes in shape, affecting the crown's integrity, retention and functional performance [25]. However, it is important to note that in the BioFlx group, the minimally increased distortion did not significantly impact retention and clinical performance. Therefore, despite the slightly higher deformation, the BioFlx crowns demonstrated acceptable retention and fulfilled their intended purposes of protecting the tooth, restoring occlusion and maintaining aesthetics.

The current study has several limitations that should be acknowledged. Firstly, the study utilized a software-generated static load model and a digitally constructed simulated tooth without considering the presence of the pulp, periodontal ligament, bone and vitality in the isometric, monobloc tooth design. Secondly, a luting agent was not applied to the canal. The tooth was prepared for crown placement and scanned. Thirdly, the study focused solely on primary maxillary second molars, and including teeth with diverse morphologies might have provided a more comprehensive analysis. Thus, future research could aim to conduct more extensive trials that consider the characteristics of the tooth and crown, as well as the length of the root, surrounding bone and periodontal anatomy, which play a crucial role in the overall performance and longevity of dental restorations. Additionally, the specific mechanical properties of these materials should be assessed on an individual basis for each unique dental application, as they can vary based on factors such as composition, processing and loading conditions.

5. Conclusions

In summary, this study provides valuable insights into the mechanical behavior of BioFlx crowns when used to restore endodontically treated primary molars. The FEA findings suggest that BioFlx crowns can serve as a viable alternative to zirconia and stainless-steel crowns in terms of mechanical performance, particularly when GIC is used as the core build-up material. However, further comprehensive studies are necessary to evaluate the clinical performance of Bioflx crowns in real-world clinical scenarios. It is important to consider additional factors such as retention, marginal integrity, aesthetics, patient satisfaction and longevity when considering BioFlx crowns as a potential replacement. Overall, this study provides a foundation for future research in this field, and in the future, conducting more in-depth studies to assess the clinical performance of BioFlx crowns in practical settings would be highly beneficial.

AVAILABILITY OF DATA AND MATERIALS

Not applicable.

AUTHOR CONTRIBUTIONS

TL and NR—designed the research study. TL—performed the research. VP—provided help and advice on execution of the study. VM and RP—analyzed the data. TL, VM, MC, GM and SH—wrote the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

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CONFLICT OF INTEREST

The authors declare no conflict of interest. Giuseppe Minervini is serving as one of the Editorial Board members of this journal. We declare that Giuseppe Minervini had no involvement in the peer review of this article and has no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to AS.

SUPPLEMENTARY MATERIAL

Supplementary material associated with this article can be found, in the online version, at https://oss.jocpd.com/files/article/1852222618483998720/attachment/Supplementary%20material.docx.

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