A Novel Computational Approach to CAD-Driven Biomechanical Analysis of 3D-Printed Dental Crowns

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Abstract

Stereolithography (SLA) resin 3D printing technology has changed many aspects of dental crown fabrication. The current work focuses on the finite element analysis study of mechanical behavior in under-axial loading conditions and quantifies Von Mises stresses in a SLA resin 3D printed crown. The results illustrated severe stress concentrations at the tips of the cusps with peak Von Mises stress around 136.3 MPa and maximum deformation around 0.02653 mm. The results showed that SLA resin crowns had higher levels of stress (75.0 MPa) compared to zirconia (65.0 MPa) and ceramic (70.0 MPa) crowns, indicating that the danger of failure under the influence of stressful factors is greater for this type of crown material. Still, SLA resin crowns showed lower deformation than zirconia (0.030 mm) and ceramic (0.035 mm). However, the need for shape optimization and improvement in material to increase the lifetime of SLA resin crowns was shown. However, there is a need for further research to match their performance to that of conventional materials. The future line of work should consider the development of new resin formulations that would better mechanical properties and the optimization of printing parameters to reduce stress and deformation in 3D-printed crowns.

Keywords

Forecasted Economics, Artificial Neural Networks, Open Government Data, Business Dynamics

1. Introduction

Prosthodontics, as a branch of dentistry, has experienced a sea change with the assimilation of additive manufacturing technologies, more commonly described as 3D printing [1]. Wide applications benefit from additive manufacturing, including the communication sector [2, 3, 4, 5, 6]. These have brought a revolution in the fabrication of dental prostheses [7]. SLA resin 3D printing is one of the best technologies in producing functional and esthetical dental crowns due to its very high level of accuracy and smooth finish [8]. The high degree of customization that 3D printing allows entails the production of dental restoration on a need-to basis. However, understanding the mechanical behavior of 3D-printed crowns under physiological loading is an essential aspect in ensuring durability and clinical efficacy [7, 9, 8, 10] and quality [11]. Tahayeri et al. [12] in the study comparative analysis carried out between 3D-printed and conventionally cured provisional crown materials displayed within-materials comparable mechanical properties, respectively, that suggest the potential viability of additive manufacturing within dental prosthetics. The introduction of such technologies into dentistry has revolutionized the methodologies used in fabricating prosthetics. The 3D-printed provisional crown materials compared to the traditionally cured provisional crown materials have shown both materials to have a similar set of mechanical properties and the data satisfied [8, 12, 13, 14].

This means that the process of additive manufacturing can indeed be carried out for dental materials. Their applications in dentistry have, therefore, advanced the ways and means in prosthesis manufacture. Revilla-León and Özcan (2018) [15] in their study provide a comprehensive overview of various 3D printing technologies used in prosthodontics with their advantages and limitations. They underscore the potential of the technologies for enhanced precision and efficiency in the production of dental restorations. The mechanical properties of 3D-printed dental materials have been widely studied [16]. The oral environment provides a complex biomechanical milieu with forces exerted on dental restorations. The value of the results of these studies is immense in predicting clinical performance [17, 18, 19] as well as reliability of these prostheses [20, 21]. Finite element analysis is a very strong non-invasive tool that helps to understand the mechanical behavior of dental structures and restorations [22, 23, 24]. The adoption of 3D printing in dentistry has been extensively studied, with a focus on both the mechanical and biological properties of the materials used. For instance, Atria et al [25] evaluated the mechanical properties of various 3D-printed resins for provisional dental restorations, finding that the experimental Permanent Bridge (PB) resin demonstrated superior mechanical properties compared to other commercially available resins. The use of high-fidelity FEA for different fields [26, 27, 28, 29], specific in the bio mechanics material like dental prostheses is still an emerging area of research, even though it has been extensively

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used in conventional prosthodontics. The unique microstructure of the printed resins and associated material properties call for a rethink of established biomechanical principles in crown design and manufacture. Previous studies have shown that stress distribution can vary significantly with different cusp angles in dental crowns [30]. This study employs finite element analysis (FEA) to investigate the mechanical behaviour of SLA resin 3D-printed dental crowns under vertical loading conditions. Achour et al. [31] studied FEA applications in the realm of dental implant research. It was determined that the tool is helpful in optimizing implant design as well as predicting its clinical performance. However, a significant shortage of works notes stress analysis of 3D-printed dental crowns through high-fidelity FEA models. Porojan and Topală [32] used the finite element method to study the failure mechanism of monolithic posterior aesthetic crowns; needful material choice and designs that would minimize stress concentrations were being discussed. Yoon et al. [33] further emphasized that crowns made from materials with higher elastic moduli, such as ceramics, were more effective in reducing stress on tooth structures. The convergence of additive manufacturing and FEA has opened new avenues for optimizing dental prosthetics, as discussed by [34], who explored the effects of different materials and designs on stress distribution in dental restorations. This paper tries to fill this gap by running advanced finite element high-fidelity models to detail the stress analysis in SLA resin 3D-printed dental crown structures. In this study, the various loading scenarios have been applied using the Abaqus software package for making judgments on the distribution of stresses and deformation patterns in 3D-printed crowns. This paper gives new perspectives on the mechanical behavior of the specificities and functioning of the characteristics of SLA resin crown by means of better design and fabrication techniques that provide better clinical results. It presents a comprehensive FEA study on SLA resin 3D printed dental crowns under normal loading conditions to provide insights into their mechanical behavior. But as per this research, the SLA resin crowns can have some prospects in dental restorations, but in many aspects, they are behind the materials like zirconia and ceramic.

2. Materials and Methods

2.1. Crown Design and Material Properties

A three-dimensional model of a mandibular first molar crown was created using computer-aided design (CAD) software. The crown geometry was based on average anatomical measurements derived from a sample of 50 adult human molars, as reported by [30] as shown in Figure (1).

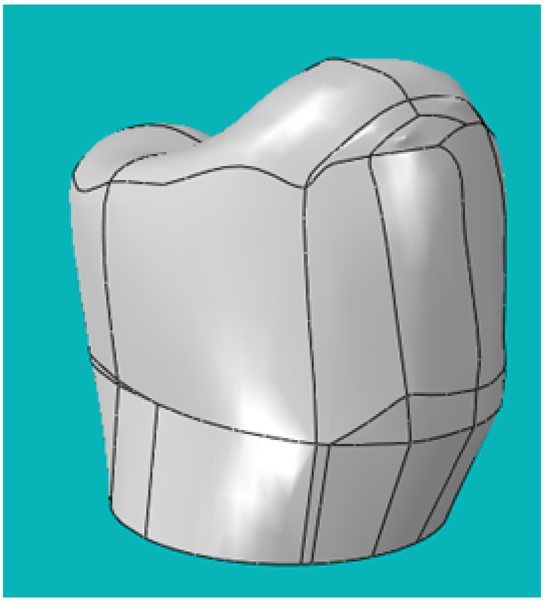

Figure 1: Crown implement geometry

The material properties used in the FEA model were based on a photopolymerizable resin specifically designed for 3D printing of dental prostheses (NextDent C&B, 3D Systems). The key mechanical properties, as reported by the manufacturer and verified through independent testing, as reported from the previous study [35] where the behavior is like the composite material and has the elastic properties [36, 37].

2.2. Finite Element Model Development

The 3D model was imported into Abaqus CAE (Dassault Systèmes) for mesh generation and analysis. A tetrahedral mesh was generated, consisting total number of element 25570 linear tetrahedral elements of type C3D4 as shown in the Figure (2). A mesh convergence study was conducted to ensure result accuracy while maintaining computational efficiency [23, 24], while an interesting improvement can be obtained by using neural approaches [38, 39]. Boundary conditions were applied to simulate the crown cemented to an idealized tooth preparation. The interface between the crown and the tooth preparation was modeled as a perfectly bonded connection [40]. The base of the tooth preparation was fixed in all degrees of freedom to simulate the constraints provided by the surrounding bone structure.

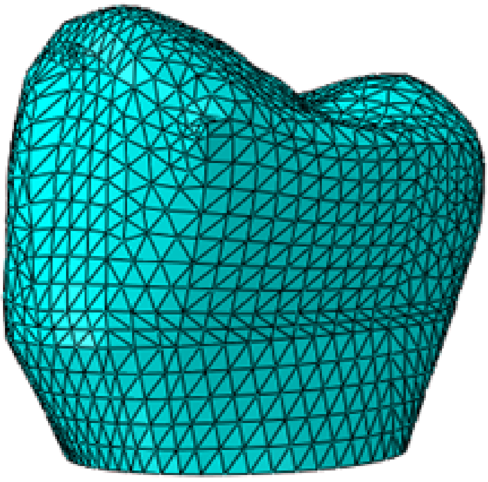

Figure 2: Mesh generation

2.2.1. Loading Conditions

The distinct loading scenarios were simulated to represent a range of physiological and parafunctional forces, vertical load: A total force of 600 N was applied uniformly across the occlusal surface as shown in Figure (3), simulating normal mastication forces [33].

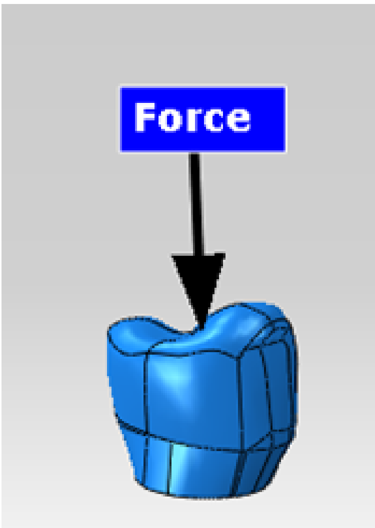

Figure 3: Force applied on the Crown

2.2.2. Analysis Parameters

The analysis was conducted using Abaqus/Standard, employing a static, linear elastic model. The von Mises stress criterion was used as the primary metric for evaluating stress distribution within the crown. Additional output variables included maximum principal stress, minimum principal stress, and total deformation.

3. Results and Discussion

3.1. Stress Distribution Patterns

The finite element analysis (FEA) conducted under vertical loading conditions revealed distinct stress distribution patterns in the 3D-printed dental crown. Utilizing the von Mises stress criterion [41, 42], the analysis identified areas of high stress concentration, primarily at the cusp tips and the central fossa region of the crown. • **Stress Concentrations:** Under a vertical load of 600 N, stress was predominantly concentrated at the mesio-buccal cusp tip. The maximum von Mises stress recorded was approximately 136.3 MPa as shown in Figure (4). This high-stress concentration at the cusp tips indicates that these areas are critical points that bear the highest loads during normal mastication, making them susceptible to potential stress-induced failures.

The stress contour plots visually demonstrate the regions where the material is most likely to experience failure, emphasizing the importance of these findings in optimizing the design of dental crowns to enhance their durability.

3.2. Deformation Analysis

The deformation analysis provided additional insights into the structural integrity of the 3D-printed dental crown under the applied load. The results indicated that the deformation patterns closely followed the stress distribution, with the highest deformation observed at the same critical regions identified in the stress analysis. The deformation distribution under a vertical load scenario shows that the highest deformation occurs at the cusp tips, particularly the mesio-buccal cusp tip, and the central fossa. Maximum Deformation, vertical load scenario resulted in a maximum deformation value of 0.02653 mm as shown in Figure (5).

This value is within the acceptable range for dental restorations, indicating that the crown can withstand functional loads while maintaining its structural integrity.

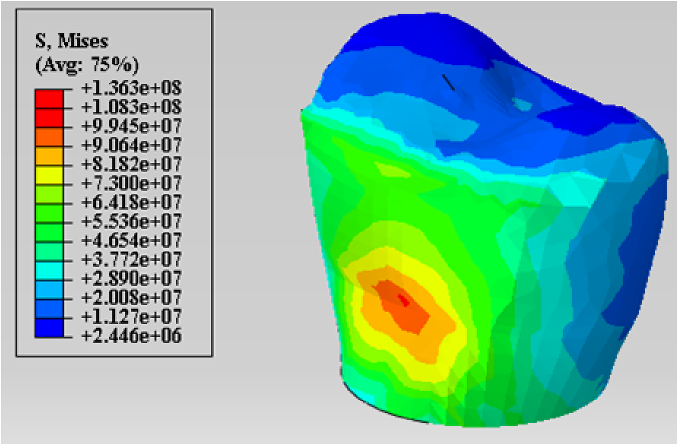

Figure 4: Von-mises stress for the crown

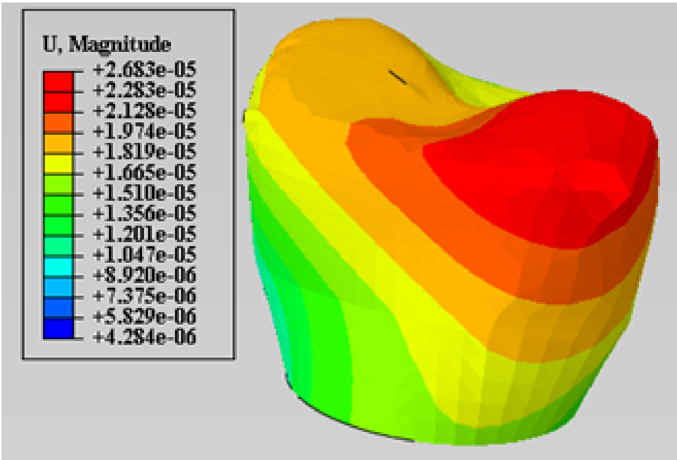

Figure 5: Deformation of the crown

4. Discussion

The current study was aimed at conducting finite element analysis to examine the mechanical behavior of SLA resin 3D-printed dental crowns under a vertical loading condition. Important results can be derived by this means regarding the patterns of stress distribution and deformation, which could possibly be predicted due to this new manufacturing way, in order to make possible further improvements on such a material. **Comparison with Past Studies:** In this section, the current results are compared in detail with the findings from past studies for different crown materials such as zirconia and ceramic. The quantities of importance for the stress and deformation from these comparisons are listed in Table 1.

Implications of Stress Results: The von Mises stress analysis as illustrated in Figure (6) showed that the SLA resin crowns have elevated stress concentrations, especially at the cusp tips, compared to zirconia and ceramic. The maximum registered stress for SLA resin was 136.3 MPa, as opposed to 65.0 MPa for zirconia and 70.0 MPa for ceramic. These results indicated that SLA resin crowns might have a higher tendency for specific areas of stress-related failures, and therefore the optimization of design was required in order to ensure their durability.

Deformation Analysis: From Figure (7) can be observed that the deformation study revealed that the maximum deformation of SLA resin crowns was 0.02653 mm, lower than that found for zirconia at 0.030 mm, followed by ceramic at 0.035 mm. This indicates that stress concentrations are higher and deformation is lower in loading conditions for SLA resin crowns within clinically accept-

Table 1
Comparison with Past Studies

Material	Maximum von Mises Stress (MPa)	Maximum Deformation (mm)	Key Findings	Reference
SLA Resin (Present Study)	136.3	0.02653	Higher stress at cusp tips, moderate deformation	This Study
Zirconia	65.0	0.030	Lower stress concentration, high durability	Yoon et al. [33]
Ceramic	70.0	0.035	Balanced stress distribution, suitable for crowns	Porojan and Topală, [32]

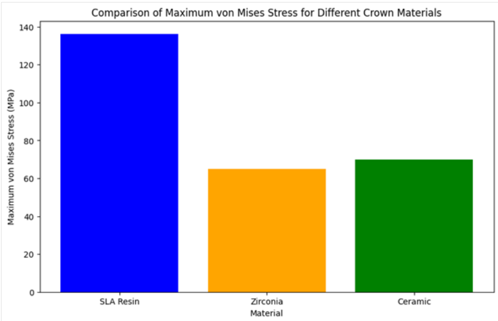

Figure 6: Comparison of Maximum von Mises Stress for Different Crown Materials

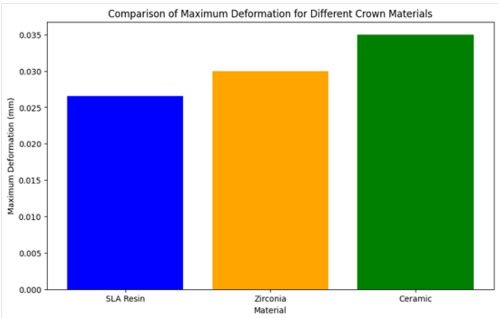

Figure 7: Comparison of Maximum Deformation for Different Crown Materials

able levels. Lower values of deformation indicate that SLA resin crowns would still be stable in their structure under functional loads and can be applied in temporary or provisional restorations.

5. Conclusion

This study presents a comprehensive finite element analysis (FEA) of SLA resin 3D-printed dental crowns under vertical loading conditions, revealing key insights into their mechanical behavior. The analysis indicates that while SLA resin crowns show promising potential for dental restorations, there are notable areas for improvement, especially when compared to traditional materials like zirconia and ceramic.

• **Important Findings:**

1. Stress Distribution: From the von Mises stress analysis, it has been revealed that increased levels of stresses occurred at the cusp tips in the SLA resin crowns, with a maximum of around 136.3 MPa. This is indeed much higher in comparison with those observed for zirconia and ceramic crowns, respectively, the value indicating a much higher susceptibility to stress-induced failures of the SLA resin crowns

2. Patterns of Deformation: The highest deformation that was recorded on SLA resin crowns was 0.02653 mm, which was just slightly lower when compared with that from both zirconia and ceramic crowns, again confirming the fact that SLA resin crowns can withstand the dynamic behavior of forces applied during normal functioning of the system.

• **Future Research Directions** , Future research should aim to: Explore New Materials: Investigate advanced photopolymerizable resins with superior mechanical properties to reduce stress and deformation. Optimize Printing Parameters: Study the effects of different printing parameters, such as layer thickness and orientation, on the mechanical properties of 3D-printed crowns. Conduct Long-term Clinical Studies: Perform long-term clinical trials to validate the in-vivo performance of SLA resin crowns and their suitability for permanent restorations. In conclusion, while SLA resin crowns offer a viable solution for dental restorations, particularly for temporary and provisional applications, further optimization in design and material properties is essential. Continued research and development in additive manufacturing technologies will be crucial in advancing the clinical effectiveness and durability of 3D-printed dental prostheses.

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