COMPARATIVE FINITE ELEMENT ANALYSIS OF STRESS DISTRIBUTION OF DIFFERENT IMPLANT-SUPPORTED CROWN AND ABUTMENT MATERIALS

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COMPARATIVE FINITE ELEMENT ANALYSIS OF STRESS DISTRIBUTION OF DIFFERENT IMPLANT-SUPPORTED CROWN AND ABUTMENT MATERIALS

ABSTRACT

This study aimed to evaluate the stress distribution of three-dimensional (3D) printed ceramic filled hybrid materials and zirconia as abutments and implant-supported crowns using a finite element study model. Five groups of materials were: computer-aided design and computer-aided manufacturing (CAD/CAM) zirconia implant-supported crown with CAD/CAM zirconia custom abutment (ZR-ZR); 3D printed VarseoSmile® Crown Plus implant-supported crown with CAD/CAM zirconia custom abutment (VSC-ZR); CAD/CAM zirconia implant-supported crown with 3D printed VarseoSmile® Crown Plus custom abutment (ZR-VSC); 3D printed VarseoSmile® TriniQ® implant-supported crown with CAD/CAM zirconia custom abutment (VST-ZR); and CAD/CAM zirconia implant-supported crown with 3D printed VarseoSmile® TriniQ® (ZR-VST) custom abutment. The implant-supported crown of a mandibular first molar was designed and modelled in computer-aided design (CAD) software, and analysed using finite element analysis (FEA) ANSYS Workbench 2021 R1 software. All the materials were considered homogenous, isotropic, and linearly elastic. A 600N vertical load (Load Case 1) was applied to the central axis of implant onto the crown, while a 225N oblique load (Load Case 2) was applied 45° to the central axis of implant onto the crown. The von Mises stress was recorded at crown, cement between crown and CAD/CAM custom abutment, CAD/CAM custom abutment, cement between CAD/CAM custom abutment and titanium base (Ti-base) abutment, abutment screw, titanium base abutment, fixture, cortical, and cancellous bone. The von Mises stress percentage difference was compared to the control group ZR-ZR. The stress concentration areas were indicated by colorimetric map. At the crown, Group ZR-VST had the highest von Mises stress (214.39 MPa; 112.72 MPa), while Group

VST-ZR had the lowest (173.66 MPa; 101.58 MPa) in Load Case 1 and 2, respectively. The stress concentration areas were the crown's occlusal area, the cement layer of the neck and top region of the abutment, top region of titanium base abutment, the internal connection to the abutment screw, the collar area at gingival level, first thread of abutment screw, and cervical area of titanium base abutment. At the CAD/CAM custom abutments, Groups ZR-VSC and ZR-VST demonstrated the lowest stress in Load Case 1 and 2, which were 46.66 MPa and 44.62 MPa; 45.34 MPa and 41.95 MPa, respectively. The cement between the crown and the CAD/CAM custom abutment showed the lowest stress in Group ZR-VSC (28.19 MPa) and Group ZR-VST (28.92 MPa) in Load Case 1. In Load Case 1, the cement between the CAD/CAM custom abutment and the Ti-base abutment demonstrated the greatest stress in Groups ZR-VSC (70.14 MPa) and ZR-VST (72.52 MPa), similarly observed in Load Case 2 (Group ZR-VSC:54.72 MPa; Group ZR-VST: 57.76 MPa). The stress at the fixture in the cortical and cancellous bones was comparable across all groups under both loads. In conclusion, the combination of implant-supported crown and abutment with different moduli of elasticity positively influences stress distribution at the crown, cement between crown and CAD/CAM custom abutment, CAD/CAM custom abutment, abutment screw, cement between CAD/CAM custom abutment and Ti-base abutment, Ti-base abutment and fixture, but no effect on stress distribution in the peri-implant bone structure.

Keywords: Finite Element Analysis, 3-dimensional Printed Hybrid Materials, Computer-aided design and computer-assisted manufacturing (CAD/CAM) zirconia, Custom Abutment, Stress Distribution

ANALISIS “FINITE ELEMEN” PERBANDINGAN PENGAGIHAN TEKANAN BAGI BAHAN KORONA DAN ABUTMEN YANG DISOKONG IMPLAN BERBEZA

ABSTRAK

Kajian ini bertujuan untuk menilai pengagihan tekanan bahan hibrid yang diisi seramik tiga dimensi (3D) yang dicetak dan zirkonia sebagai abutment dan korona yang disokong implan menggunakan model kajian finite elemen. Lima kumpulan bahan yang digunakan adalah: korona yang disokong implan zirkonia CAD/CAM dengan abutment custom zirkonia CAD/CAM (ZR-ZR); korona yang disokong implan VarseoSmile® Crown Plus yang dicetak 3D dengan abutment custom zirkonia CAD/CAM (VSC-ZR); korona yang disokong implan zirkonia CAD/CAM dengan abutment custom VarseoSmile® Crown Plus yang dicetak 3D (ZR-VSC); korona yang disokong implan VarseoSmile® TriniQ® yang dicetak 3D dengan abutment custom zirkonia CAD/CAM (VST-ZR); dan korona yang disokong implan zirkonia CAD/CAM dengan abutment custom VarseoSmile® TriniQ® yang dicetak 3D (ZR-VST). Korona yang disokong implan pada molar pertama mandibula direka dan dimodelkan dalam perisian reka bentuk berbantu komputer (CAD), dan dianalisis menggunakan analisis finite elemen (FEA) ANSYS Workbench 2021 R1. Semua bahan dianggap homogen, isotropik, dan elastik linear. Beban vertikal 600N (Kes Beban 1) dikenakan pada paksi tengah implan ke atas korona, sementara beban serong 225N (Kes Beban 2) dikenakan 45° ke paksi tengah implan ke atas korona. Tekanan von Mises direkodkan pada korona, simen antara korona dan abutment custom CAD/CAM, abutment custom CAD/CAM, simen antara abutment custom CAD/CAM dan abutment asas titanium, skru abutment, abutment asas titanium, fixture, kortikal, dan tulang kanselus. Peratusan perbezaan tekanan von Mises direkodkan berbanding dengan Kumpulan ZR-ZR sebagai kumpulan kawalan. Kawasan kepekatan tekanan ditunjukkan oleh peta kolorimetrik. Pada korona, Kumpulan ZR-VST mempunyai tekanan von Mises tertinggi (214.39 MPa; 112.72 MPa), sementara Kumpulan VST-ZR mempunyai yang terendah (173.66 MPa; 101.58 MPa) dalam Kes Beban 1 dan 2, masing-masing. Kawasan kepekatan tekanan adalah kawasan oklusal korona, lapisan simen pada bahagian leher dan bahagian atas abutment, bahagian atas abutment asas titanium, sambungan dalaman ke skru abutment, kawasan kolar pada tahap gingiva, benang pertama skru abutment, dan kawasan serviks abutment asas titanium. Pada abutment custom CAD/CAM, Kumpulan ZR-VSC dan ZR-VST mencatatkan tekanan terendah dalam Kes Beban 1 dan 2, iaitu 46.66 MPa dan 44.62 MPa; 45.34 MPa dan 41.95 MPa. Simen antara korona dan abutment custom CAD/CAM menunjukkan tekanan terendah dalam Kumpulan ZR-VSC (28.19 MPa) dan Kumpulan ZR-VST (28.92 MPa) dalam Kes Beban 1. Dalam Kes Beban 1, simen antara abutment custom CAD/CAM dan abutment asas titanium menunjukkan tekanan tertinggi dalam Kumpulan ZR-VSC (70.14 MPa) dan ZR-VST (72.52 MPa), begitu juga dalam Kes Beban 2 (Kumpulan ZR-VSC:54.72 MPa; Kumpulan ZR-VST: 57.76 MPa). Tekanan pada fixture dalam tulang kortikal dan kanselus adalah setanding di semua kumpulan di bawah kedua-dua beban. Kesimpulannya, kombinasi korona yang disokong implan dan abutment dengan modulus elastik yang berbeza mempengaruhi pengagihan tekanan pada korona, simen antara mahkota dan abutment, abutment, skru abutment, simen antara abutment dan abutment asas titanium, abutment asas titanium, dan fixture. Walau bagaimanapun, ia tidak memberi kesan kepada pengagihan tekanan dalam struktur tulang peri-implan.

Kata Kunci: Analisis "Finite Elemen", Bahan Hibrid Cetakan 3-dimensi, Zirkonia, Abutmen Disesuaikan (CAD/CAM), Pengagihan Tekanan

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LIST OF SYMBOLS AND ABBREVIATIONS

3D	:	Three-dimensional
CAD/CAM	:	Computer-aided design and computer-aided manufacturing
CAD	:	Computer aided design
ZR-ZR	:	CAD/CAM zirconia implant-supported crown cemented to CAD/CAM zirconia custom abutment which is cemented to titanium base abutment
VSC-ZR	:	3D printed VarseoSmile® Crown Plus crown cemented to CAD/CAM zirconia custom abutment which is cemented to titanium base abutment
ZR-VSC	:	CAD/CAM zirconia implant-supported crown cemented to 3D printed VarseoSmile® Crown Plus custom abutment which is cemented to titanium base abutment
VST-ZR	:	3D printed VarseoSmile® TriniQ® crown cemented to CAD/CAM zirconia custom abutment which is cemented to titanium base abutment
ZR-VST	:	CAD/CAM zirconia implant-supported crown cemented to 3D printed VarseoSmile® TriniQ® custom abutment which is cemented to titanium base abutment
Ti-Base	:	Titanium base abutment
FEA	:	Finite element analysis
AM	:	Additive manufacturing
SM	:	Subtractive manufacturing
ASTM	:	American Society of Testing and Materials

SLA	:	Stereolithography
2D	:	2-dimensional
DLP	:	Digital light processing
UV	:	Ultraviolet
cpTi	:	Commercially pure Grade IV titanium
Ti-6Al-4V	:	Grade V titanium alloy
Y-TZP	:	Yttria-stabilized tetragonal zirconia
HPPs	:	High-performance polymers
UCLA	:	University of California Los Angeles Abutment
FDP	:	Fixed dental prostheses
IAC	:	Implant-abutment connection
PICN	:	Polymer-infiltrated ceramic networks
FE	:	Finite element
STL	:	Standard tessellation language
STP/STEP	:	Standard for the Exchange of Product

CHAPTER 1: INTRODUCTION

1.1 Introduction

The inclusion of digital workflow in dentistry has led to further development of computer-aided design and computer-aided manufacturing (CAD/CAM) technology. It includes subtractive (SM) or additive manufacturing (AM) technology, or a combination of both, to manufacture dental restorations. Nevertheless, the shortcomings of subtractive or milling technology include material waste, the tendency to induce microcracks, and the lack of surface detail reproduction depending on the size of the milling tools. The bur size used in the milling process also limits the design of subsequent restorations. Another alternative to milling is AM technology, which has been successfully introduced in manufacturing resin and metal prosthesis (Beuer et al., 2008; Hoang et al., 2015; Huang, 2003; Soumeire & Dejou, 1999; Strub et al., 2006; Zeng et al., 2015) .

According to the American Society of Testing and Materials (ASTM), AM is defined as "the process of joining materials to make objects from 3D model data, usually layer-upon-layer, as opposed to subtractive manufacturing methodologies." There are seven different categories classified by ASTM: stereolithography (SLA), material jetting, material extrusion, binder jetting, powder base fusion, sheet lamination, and direct energy deposition. SLA and the related digital light processing (DLP) technique are the most commonly employed methods in dentistry. Both use curable photopolymer resin, where a build plate descends in small increments and the liquid polymer is exposed to light for polymerization. In the SLA technique, the object is constructed by the ultraviolet (UV) laser or laser diode, drawing each layer of the cross section one by one. The DLP technique employs a digital projector screen to transmit a single image of each layer simultaneously across the entire build plate (Kessler et al., 2019).

AM has the potential to overcome the challenges of milling dental ceramics. It can create dental restorations with complex macro-geometries and shapes that couldn't be made using conventional machining techniques, as well as include undercuts or inaccessible areas that cannot be milled. Its benefits include mass production, time savings, and less material waste. Moreover, it also reduces the residual monomers and eliminates the need for heating materials, which benefits the surrounding tissues and prepared teeth. The internal and marginal fit accuracy is more promising due to the reduced polymerization shrinkage (Abdullah et al., 2018; Ahlholm et al., 2019; van Noort, 2012; Zhang et al., 2014). Unlike the cartridge system, this material is flexible because it does not need to remove teeth or models. Less flexibility allows for a higher filler content, resulting in improved mechanical properties. Nevertheless, in the case of AM materials, their filler content and size are restricted to maintaining a certain level of viscosity in the resin (Kessler et al., 2019; Revilla-León et al., 2019; Tahayeri et al., 2018). Due to the superior advantages compared to subtractive manufacturing, additive manufacturing of dental products has gained popularity. Additionally, there have been significant advancements in the development of additively manufactured resin materials that can be utilized for definitive prostheses (Çakmak et al., 2024; Grzebieluch et al., 2021).

Implant-supported crown has been increasingly indicated for replacement of a missing tooth. The primary cause is their ability to conserve the natural dental tissues of adjacent teeth, as well as their positive prognosis, which is supported by substantial scientific research published in the literature, including extensive clinical trials. The long-term efficacy of dental implant crowns highly depends on the fundamental biological and mechanical features of the prosthetic superstructure. The effectiveness of this treatment approach is not only dependent on the achievement of successful osseointegration, but it is also closely linked to the corresponding aesthetic of the superstructure, supra-crestal soft tissue emergence profile and functional demands (De Angelis et al., 2020; Jung et al., 2012).

Dental implant abutments serve to connect the implant fixture with the prosthetic component, ensuring stability and functional support. There are various dental materials for manufacturing dental implant abutments, including titanium, zirconia, and hybrid options. Every material has its own distinct benefits and drawbacks, which can influence the outcome of implant restorations in terms of aesthetics and longevity (Alqutaibi, 2019; Alqutaibi et al., 2021).

Titanium abutments are widely used as implant abutments because of their well-established clinical success and high survival rates. Clinical studies show that fixed implant reconstructions supported by titanium abutments had very high survival rates. In a recent systematic review, it is found that metal abutments supporting fixed implant reconstructions have only a limited number of complications. The abutment screw loosening is the most common technical issue encountered with this particular abutment (Andersson et al., 1995; Pjetursson et al., 2007; Sailer, Philipp, et al., 2009). Nowadays, the aesthetic outcome is also one of the important criteria for the clinical success of an implant-borne reconstruction. The dark greyish appearance of metal abutments is one of their main disadvantages. Numerous studies have demonstrated that metal abutments can result in a greyish discolouration surrounding the mucosa of a dental implant. Therefore, metal abutments have limited indications in aesthetic zones, despite being extremely stable from a technical standpoint (Jung et al., 2007; Park et al., 2007). Although titanium oral implants have shown significant development and survival rates of 95% or greater over a period of 5-10 years, there is an increasing demand for metal-free alternatives. Besides, there is an aspect to consider: the possibility of titanium particle release, which could result in hypersensitivity or allergy to titanium (Callejas et al., 2022; Goiato et al., 2014; Müller & Valentine-Thon, 2006; Sicilia et al., 2008) .

Alternatively, ceramic abutments made out of the high-strength ceramics alumina and zirconia are developed. Compared to metal abutments, ceramic abutments provide more clinical benefits. First and foremost, their aesthetic benefit and lessening effect on mucosal discoloration are well documented. Ceramic abutments induce significantly less mucosal discoloration than metal abutments. It is also found that there is less bacterial adhesion and biofilm formation on ceramics such as zirconia than on titanium. Ultimately, the soft tissue integration of the ceramics alumina and zirconia is comparable to that of titanium (Abrahamsson et al., 1998; Hashimoto et al., 1988; Jung et al., 2008; Kohal et al., 2004; Prestipino & Ingber, 1993a, 1996; Roehling et al., 2017; Scarano et al., 2004). Ceramics' mechanical behaviour is limited by their brittleness and reduced resistance to tensile stresses. The presence of micro-structural defects in the material may lead to the formation of cracks when subjected to tensile forces. They are brittle, more prone to fatigue, and hence less resistant to fractures (Apicella et al., 2011; Belser et al., 2004).

Additively manufactured definitive resins are the new materials introduced in dentistry for full and partial coverage restorations on natural teeth. Their usage has now been proposed for implant-supported restorations. Definitive resins can be either commercialized as composite resins or hybrid composite resins incorporating ceramic particles. One of the biggest advantages of resin-based materials includes acting as a shock absorber dissipating great masticatory forces which may be destructive to the bones due to lack of periodontal ligaments and proprioception. These new materials have gained great interest due to their high resistance to fractures, pleasant aesthetics, accurate measurements with the implant, and biocompatibility (Çakmak et al., 2022; Donmez & Okutan, 2022; Graf et al., 2022; Roberts et al., 2018; Rosentritt et al., 2017). However, the stress distribution of different combinations of crown and abutment materials in implants and peri-implant bone components remains unclear. This study aims to evaluate the stress distribution of 3D printed ceramic filled hybrid materials used as CAD/CAM custom abutments and implant-supported crowns, and compare them with CAD/CAM zirconia, while properly citing relevant literature.

1.2 Research Question

- Can the force transferred to the various interfaces in dental implant-supported restorations and result in stress be reduced by implementing novel designs, such as incorporating 3D printed ceramic filled hybrid materials substrates with zirconia, to enhance the biomechanical compatibility and shock absorption capabilities of these prostheses?
- Can the force transferred to the peri-implant bone in dental implant-supported restorations and result in stress be reduced by implementing novel designs, such as incorporating 3D printed ceramic filled hybrid materials substrates with zirconia, to enhance the biomechanical compatibility and shock absorption capabilities of these prostheses?

1.3 Aim of Study

- To evaluate the stress distribution at the different components of implant system and surrounding bones using different combinations of two different materials which are 3D printed ceramic filled hybrid materials and CAD/CAM zirconia.

1.4 Objectives

- To evaluate the stress distribution at peri-implant bone with two 3D printed ceramic filled hybrid materials and CAD/CAM zirconia as CAD/CAM custom abutment and crown materials.

- To determine the stress distribution at various interfaces of implant-supported prosthesis including the crown, cement layers, CAD/CAM custom abutment, abutment screw, Ti-base abutment & fixture. This is done using different combinations of 3D printed ceramic filled hybrid materials and CAD/CAM zirconia for abutment and crown materials.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction of Dental Implant

The field of dental implantology has a significant historical background, as early endeavours to replace teeth can be traced back thousands of years in ancient civilizations. In 1965, Dr. P. Branemark developed an implant system using pure titanium screws that was first placed in his patient. This made a significant contribution to modern dental implantology. These 4 implants were placed in a patient with severe jaw and chin deformities, tooth agenesis, and misaligned teeth and were noted to fuse with bones in 6 months. They remained intact in situ for the next 40 years. This accomplishment gave rise to the principle of osseointegration, which denotes that the implant and the neighbouring bone form a structural and functional connection under loading. Numerous implant systems and protocols have a significant impact on osseointegration, transforming the field of dental rehabilitation (Brånemark, 1983).

Earlier, Branemark implants were mainly used for securing mandibular complete prostheses in place. The application of dental implants has expanded over the ensuing decades to encompass complicated maxillofacial prostheses, removable complete implant-retained and supported overdentures, fixed partial dentures, and crowns. Its reliable results in supporting a wide range of dental prostheses led to its implementation in prosthodontics (Albrektsson & Donos, 2012).

2.2 Components of Dental Implant

Dental implants comprise several primary components, such as the crown, abutment, and fixture. The fixture is surgically inserted into the jaw bones and serves as a foundation for implant superstructures. The abutment is the connection between the implant crown and fixture, protruding from the gingiva and supporting the crown. It ensures the stability and alignment of the crown. The crown is the prosthesis to replace a missing tooth and could be made of different materials, such as metal, porcelain, or ceramics. It mimics the appearance and performance of a natural tooth to improve function and aesthetics.

2.3 Classification of Implant-Supported Crown

2.3.1 Types of Retention

2.3.1.1 Screw-retained

Single-unit, multiple-unit, and cross-arch fixed dental prostheses are examples of screw-retained abutments. On of the main advantages is the screw-retained abutments are preferable for long-span prostheses due to easier maintenance and a reduced risk of complications. It is also applicable to cantilever prostheses due to the ease of obtaining adequate retention to compensate for the leverage of extension and the extra caution of maintenance. Its retrievability is more predictable. Furthermore, it requires minimal interocclusal space, of 4 mm (Aglietta et al., 2009; Buser et al., 1991; Chee & Jivraj, 2006; Salvi & Brägger, 2009; Shadid & Sadaqa, 2012). Sailer et al. observed that the survival rate of screw-retained partial fixed dental prostheses (FDP) was significantly higher than that of cement-retained prostheses over a five-year period, at 98% and 96.9%, respectively. However, the expected occurrence of technical issues during a 5-year period was higher for screw-retained abutments compared to cement-retained abutments, with rates of 24.4% and 11.9%, respectively. Mechanical complications include the fracture of ceramics, abutments, frameworks, implants and screws. The disadvantages also include a time-consuming procedure, increased cost, and the presence of a screw channel that cause occlusal interference, especially in posterior sites. Overall, it was shown that the complication rate in screw-retained full and partial FDPs was frequently higher for cement-retained abutments. The screw-retained abutments did not demonstrate a 5-year biological complication rate compared to the cement-retained abutments (2.8%)(Sailer et al., 2012) .

2.3.1.2 Cement-retained

The pros of a cement-retained abutment are that it can compensate for implant placement that is not in the prosthetically ideal position, it has a good passive fit, it doesn't have a screw channel, and it's easy to control occlusion in an intact occlusal table. The major drawback, broadly discussed, was excess cement and the inability to remove it, leading to peri-implantitis and mucositis. Furthermore, the downsides from a biological point of view, such as marginal bone loss greater than 2 mm, are common. There is a higher chance of a microgap being present between the abutment and the superstructure, which acts as a reservoir for biofilm. Thus, the cementation should be done appropriately and strictly follow the protocol, with the cementation margins at the equivalent or supracrestal soft tissue level. At the same time, from technical point of view, reports of abutment loosening were more prevalent in cement-retained abutments. Cement-retained abutments are also more difficult to repair than screw-retained abutments, according to the technical complications reported (Keller et al., 1998; Londhe et al., 2020; Quirynen & van Steenberghe, 1993).

2.3.1.3 Screw-retrievable Cement-retained (SRCR) Restorations

It is combination of cement- and screw-retained retention. Its advantage includes eliminates the risk of subgingival cement, as the components are cemented extraorally. Besides, the cement layer also works as an interface to distribute the force evenly while the screw access channel is retrievable. The use of prefabricated titanium attached to the superstructure with luting cement instead of a cast high noble abutment for screw-retained restorations helps to save the cost of production (AlHelal et al., 2017; Conejo et al., 2017; Heo & Lim, 2015; Lin et al., 2014; Malpartida-Carrillo et al., 2020; Proussaefs & AlHelal, 2018; Selz et al., 2016; Stimmelmayr et al., 2017). Its disadvantage is that the presence of screw access channels interferes with occlusal morphology and disrupts the continuity of the structural ceramic, which reduces the material's longevity and fracture resistance.

2.3.2 Types of Crown Materials

2.3.2.1 Metal-Ceramics

The crown materials are one of the potential factors affecting the outcomes of implant-supported crowns. Metal-ceramics have historically dominated clinical applications. The study by Jung et al. reported a significantly high survival rate of 95.8%. It reported satisfactory clinical outcomes and mechanical stability. Based on a systematic review and meta-analysis of randomised controlled trials by Ahmed et al., metal-ceramic crowns and all-ceramic crowns exhibited similarly acceptable outcomes in regard to prosthesis failure, mechanical and biological complication rates, and patient satisfaction. Its estimated 5-year survival rate of 98.3% was considered as the gold standard. A recent systematic review revealed that metal-ceramic implant-supported restorations have a similarly outstanding 5-year survival rate to all-ceramic restorations. There was a systematic review and meta-analysis by Hu et al. demonstrated no significant difference between ceramic and metal ceramic implant-supported crowns in terms of survival rate, marginal bone loss, pocket probing depth, or mucosal discoloration. Metal-ceramics implant-supported crowns showed better marginal adaptation than all-ceramics. However, aesthetics is compromised, especially in colour matching. Current evidence suggests that metal- ceramic implant-supported crowns may have a higher survival rate than all-ceramics (Alqutaibi et al., 2021; Hu et al., 2020; Jung et al., 2012; Pjetursson, Valente, et al., 2018; Rabel et al., 2018). Conversely, metal ceramic crowns had a substantially reduced failure rate than porcelain-fused-to-zirconia implant crowns caused by veneer ceramic cracks. However, further studies that involve larger sample sizes are needed. On the other hand, there was a study of ceramic veneering reported as the most frequent complication, occurring in 16.7% of cases within 5 years (Pjetursson et al., 2014).

2.3.2.2 Veneered Ceramics

Nevertheless, Pjetursson's research indicated that zirconia-ceramic implant-supported crowns are just as good an alternative to metal-ceramics as metal-ceramics in terms of similar biological complications and aesthetics. Several systematic reviews also reported that all-ceramic implant crowns had a comparable survival rate of 95.8% after 5 years and slightly reduced to 94.4% after 10 years. However, in Rammelsberg's study, all-ceramics had a higher incidence of failure than metal-ceramics. The mechanical complications related to crown fracture occurred more frequently in zirconia-ceramics (Jung et al., 2012; Pjetursson, Valente, et al., 2018; Rabel et al., 2018; Rammelsberg et al., 2020). Veneered ceramics implant-supported crowns observed a remarkably greater rate of chipping off compared to monolithic. Zirconia and lithium disilicate have a higher potential risk for chipping, especially in cases of full coverage compared to partial coverage (Pjetursson et al., 2021; Rammelsberg et al., 2020).

Mechanical problems happen more often with implant-supported all-ceramic crowns that use the bilayering technique and Y-TZP as the core material. The most prevalent technical complication observed was chipping, with a complication rate of 9% after 5 years. Moreover, a greater percentage of porcelain-fused-to-zirconia implant crowns fractured specifically due to fractures in the veneering ceramic in comparison to metal-ceramic crowns (Rabel et al., 2018).

2.3.2.3 Monolithic Ceramics

Monolithic zirconia crowns have a higher flexural strength and fracture resistance than bilayered ceramics, reducing the chipping and fracture risks observed with veneered ceramics. The common complications seen in monolithic ceramic implant-supported crowns were screw loosening and debonding at the titanium base abutment. The highest rate of screw loosening is presented in monolithic zirconia implant-supported crowns

(2.25% in 32 studies with 1153 implant-supported SCs) reported an annual rate of 0.44%. and the second-highest rate of loss of retention is fracture of luting cement, with 4.44%, reported for monolithic zirconia implant-supported crowns. This material is unyielding and vulnerable to excessive occlusal force, which can cause the implant-supported prostheses to crack and break due to the lack of proprioceptive feedback from periodontal ligaments (Hamza & Sherif, 2019; Joda et al., 2015; Lemos et al., 2022; Pjetursson et al., 2021; Rosentritt et al., 2018; Spitznagel et al., 2022; Zhang et al., 2013).

2.3.2.4 CAD/CAM Resin Composites

Resin composites were more preferable in additive manufacturing than glass ceramics due to their low abrasiveness to opposing teeth and the capability to absorb functional stress. 3D printing provides greater accuracy, repeatability, speed, and cost-effectiveness. Clinical research demonstrates the potential of resin composites as a material that may address biomimetic principles of tissue preservation and validates the favourable performance of such indirect resin composite restorations. According to several in vitro studies, the mechanical properties, such as fracture and fatigue strengths, of resin composite CAD/CAM materials, as well as clinical performance has a favourable short-term survival rate (Abdullah Alshamrani et al., 2023; Edelhoff et al., 2023; El-Damanhoury et al., 2015; Komine et al., 2020; Kunzelmann et al., 2001; Magne et al., 2002; Shembish et al., 2016; Vanoorbeek et al., 2010).The impact of ceramic nanoparticles on the characteristics of resin dental composites includes their chemical stability over time and improved mechanical properties. The 3D printed crown with additional ceramic nanoparticles showed comparable results in fracture resistance. (Abdullah Alshamrani et al., 2023; Moldovan et al., 2023; Singh et al., 2016). The literature showed that CAD/CAM resin composites with a relatively high flexural strength and a low flexural modulus probably due to an increased filler load and enhanced degree of cure. As previously postulated by Magne et al. , materials with a lower flexural modulus experience a bigger deformation under load and greater stress absorption compared to a higher flexural modulus (Alharbi et al., 2016; Magne et al., 2011; Sulaiman, 2020; Zimmermann et al., 2020). According to the study conducted by Valenti et al., 3D printed resin materials could be an alternative to conventionally milled one (Valenti et al., 2022).

2.4 Implant Abutment

The success of a dental implant restoration is multifactorial. Different types of abutment materials and designs play a crucial role in achieving aesthetic and functional harmony in implant prostheses.

The implant abutment is an integral part of the dental implant that emerges through the peri-implant gingival tissues connecting the implant platform and prostheses. A correctly chosen implant abutment will assure outstanding functional stability, sufficient soft tissue thickness, and a harmonious and well-proportionate emergence profile (Stoeva et al., 2022).

The superstructure, also known as the metal framework, is attached to the implant abutment. It is mainly to provide retention in removable prostheses and also serve as the framework for a fixed prosthesis. An implant prosthetic superstructure can be vulnerable to excessive masticatory stresses, making it a potential weak point. Excessive loading can result in mechanical complications such as abutment screw loosening, screw fracture and abutment fracture (Carossa et al., 2022).

2.4.1 Classification of Dental Abutments

There are numerous classifications of dental abutments that are well documented in the literature. There are different types of implant-abutment connections, methods of manufacturing, types of abutment materials, and types of retention in prostheses.

2.4.1.1 Implant-Abutment Connections

(a) ***External Hex Connection***

External hex was originally introduced with Branemark type of implants. It was long in service and implemented in a number of systems, as the abutments are interchangeable among the manufacturers. The implant-abutment interface was first introduced as a 7-mm-high external hexagon. It can be used not only as a fixature mount during the first stage of implant placement, but also as a transmucosal extension in restoring completely edentulous arches (Binon, 2000; Muley et al., 2012). The drawbacks of this design include an ineffective anti-rotational feature and the inability to withstand excessive axial forces towards the crowns. Therefore, a variety of issues may arise, including fractures or loosening of the abutment screw, fractures of the abutment, and delicate movements at the connection between the implant and the abutment. Following that, many modifications of this design came onto the market to overcome its limitations, such as tapered external hexagons, external octagons, and spline connections (Binon, 1995; Binon et al., 1994).

(b) ***Internal Hex Connection***

In order to overcome the drawbacks of the external hex, the internal hex was implemented. It was developed by Nickzick implant manufacturer in 1986. Its main functions are to maintain the integrity of the joint between implant and abutment when subjected to masticatory load and facilitate uniform distribution of force throughout the implant. Furthermore, it simplifies the procedure and armamentarium required to complete the restoration (Binon et al., 1994; English, 1992; Kallus & Bessing, 1994; Niznick, 1982; Niznick, 1991). It offers a limited interocclusal height for prosthetic components, a shielded abutment screw, resists vibration, avoids microbial invasion, and improves aesthetic outcomes by lowering the restorative interface (Binon, 2000). There are different types of internal hex designs, including the most common six-point internal hexagon, twelve-point hexagon, three-point internal tripod, internal octagon, and morse taper, all of which are well known for their superior outcomes in terms of implant survival, success, and preservation of peri-implant bone height (Goiato et al., 2015; Schmitt et al., 2014; Vetromilla et al., 2019). The concept of a friction fit connection at a two-degree and four-degree taper works as a retention feature to retain the implant abutment through surface friction. Its anti-rotational feature reduces abutment screw loosening and eliminates micromovement in the implant-abutment connection. Both Sutter et al. and Norton demonstrated the implant system's resistance to bending force by incorporating the morse taper design's vertical positioning and self-locking features. Levin et al. and Felton also proved a similar result (Chee et al., 1999; Levin et al., 2005; Merz et al., 2000; Muley et al., 2012; Norton, 1997; Norton, 1999).

2.4.1.2 Method of Manufacturing Dental Abutments

(a) ***Standard Stock Abutments***

Standard stock abutments are pre-machined by the manufacturers to reduce preparation time. They can be modified and milled by dentists or dental technologists to mimic the contour of natural teeth and improve aesthetics. They are available in various angulations, such as 0°, 15°, and 20°, to accommodate the position of fixtures. They can be fixed or removable. The fixed abutments include Snappy abutments, multi-unit abutments, Aesthetic abutments, Procera abutments, Gold adapt abutments, and single tooth abutments. Moreover, removable abutments are Locator, GPS abutments, ERA, mini ERA, BALL attachment, ZAG and others. The advantage of standard stock abutments is easy to maintain due to supragingival margin. However, it is hard to achieve a good emergence profile. Aesthetic abutments are conical abutments used in the aesthetics zone as single and multi-unit restorations, however, their collar height is uniform circumferentially and do not follow natural contour of gingival margin (Kalpana D, 2020; Shah et al., 2014).

(b) ***Custom Abutments***

Custom abutments are commonly used to correct extreme angulations, to provide proper emergence profile of supracrestal soft tissue and crown designs. They are indicated in cases of customisation for tissue collar height, crown height, interproximal distance, implant angulations, and aesthetics. They can be manufactured using the lost-wax technique, utilising the University of California Los Angeles Abutment (UCLA), gold adapt, or cast to abutments for casting. CAD/CAM technology was incorporated into the production of custom abutments in the 1980s. They utilise the digital method of impression-making and scanning, followed by milling out the prefabricated metal alloy. Improved inaccuracies occurred in the conventional casting method. There are four types of customised abutments: customised titanium abutment, customised titanium hybrid-abutment-crown, customised zirconia abutment with titanium base, and customised zirconia hybrid-abutment-crown with titanium base. They could be of the hexed type to prevent rotation in single-unit restorations, whereby the non-hexed type implant surface is indicated in multi-unit restorations by offering less rotation resistance. They exhibit a more desirable emergence profile (Elsayed et al., 2017, 2018; Kalpana D, 2020; Shah et al., 2014).

Custom titanium abutment has lower modulus of elasticity which is half of customised zirconia abutment. Hence, it generates less stress in abutment but more stress in screw, abutment and crown. It can resist deforming under higher occlusal force which is approximately 900N when occlusal vertical force beyond 220N was applied. The introduction of titanium base abutment improves mechanical performance at the implant-abutment junction and aesthetics. Custom zirconia abutment with titanium base abutment has greater fracture and flexural strength compared to custom titanium and zirconia abutment (Elsayed et al., 2017, 2018; Nouh et al., 2019a, 2019b; Peixoto et al., 2016; Yilmaz et al., 2015). Custom hybrid-abutment-crown combines custom titanium abutment and crown and then is tightened to fixture by screw. Its advantages are retrievability and indicated in limited interocclusal space where cement-retained crown could not provide adequate retention (Conejo et al., 2017; Nouh et al., 2019b; Vigolo et al., 2006). Customised zirconia hybrid-abutment-crown with titanium bases combine extraoral cementation of customised zirconia abutment to titanium base abutment and lastly screwed intraorally. This design has combination of advantages of titanium base abutment which helps in uniform stress distribution and zirconia by absorbing stress itself. This design is cost-saving and eliminates the cement interface, hence preventing peri-implantitis and mucositis The benefits also include customisation of the emergence profile and treatment modulation that requires special angulation (Adolfi et al., 2020; Elsayed et al., 2018; Nouh et al., 2019b; Pitta et al., 2018; Pumnil et al., 2022; Reich, 2015).

(c) ***Multi-Unit Abutments (MUA)***

MUA is a key to the All-on-4 ® treatment concept introduced by Maló et al. It comprises two fixtures that are placed vertically in the anterior regions, and the other two are angulated and placed posteriorly to provide the stability of the complete arch-fixed denture. It is a viable option for creating screw-retained prostheses. MUA ensures a completely passive fit of the prosthesis, even when the implant axes are significantly divergent. Moreover, they also safeguard the peri-implant soft tissues due to repeated screwing and unscrewing of the implant components (Ashurko et al., 2020; Maló et al., 2003).

2.4.1.3 Types of Abutment Materials

(a) ***Titanium***

There are numerous materials for fabricating dental implant abutments discussed in the literature. For several decades, metal-ceramic reconstructions and metallic abutments have been the norm in dental implantology. Titanium is extensively used for its simplified production process and cost-effectiveness. It is also well known for its excellent osseointegration, outstanding mechanical properties, particularly in resisting cyclic chewing loads, and exceptional resistance to corrosion. According to the ASTM, these metals are grouped as Grades I to V. Grades I to IV are pure and unalloyed, while Grade V is alloyed with the addition of 6% aluminium and 4% vanadium (Ti-6Al-4V), which is the strongest among all designed for the purpose of dental implants. There are four distinct grades of titanium that are determined by the number of impurities in the metal. Grade III and IV titanium are utilised as implants due to their favourable mechanical characteristics (Chen et al., 2020; Kim et al., 1997; Marin & Lanzutti, 2024; Nicula et al., 2007; Niespodziana et al., 2008; Niinomi & Nakai, 2011; Uporabo, 2017). Several organisations utilise the titanium alloy Ti-6Al-4V, which exhibits superior mechanical qualities compared to pure titanium. There are prefabricated and custom titanium abutments available based on different clinical scenarios. The prefabricated titanium abutments are indicated for cement retained restorations, ideal implant placement, sufficient depth, diameter, and emergence profile of the edentulous region. Conversely, custom titanium abutments can be applied whenever there is an off-axial implant in which screw access is buccally seated. They are more durable, stronger, and have a wide range of applications in the construction of prostheses with specific thicknesses, as well as in cement-retained and screw-retained restorations (Huang & Wang, 2019; Lee et al., 2010; Rodriguez et al., 2017). However, this alloy has inferior corrosion resistance and cytocompatibility properties. In addition, the grey shine from the peri-implant mucosa can sometimes be seen due to the metallic structures, especially in cases of thin phenotype gingiva, which may affect its aesthetic appearance. Allergy to titanium is another biological issue reported. However, cases of hypersensitivity to titanium are quite rare. There is a lack of scientific evidence regarding allergic reactions that led to implant loss due to the limited cases reported in the literature. Currently, there is no direct evidence showing an allergy to titanium leading to dental implant failure. Some cases have demonstrated the growth of pyogenic granulomas and haemangiomas following the initial stage of dental implant surgery and placement (Al-Shamiri et al., 2015; Cortada et al., 2000; Furrer et al., 2018; Herrero-Climent et al., 2013; Jung et al., 2007; Park et al., 2007; Velasco-Ortega et al., 2016). Several cases revealed histological findings containing metal particles, potentially due to tribocorrosion, a process that degrades mechanical characteristics due to loading, stress, or friction. However, focused histopathological analyses or specific tests are frequently unavailable or not performed routinely. Although diagnostic techniques are readily accessible, doctors and dentists often depend only on clinical and radiological assessments, neglecting laboratory testing. This is because they clinically resemble other postoperative problems, most commonly peri-implant mucositis and peri-implantitis (Poli et al., 2021).

(b) ***Alumina***

Following that, the trend has switched to ceramic abutments, especially in the aesthetic zone. In 1993, the first all-ceramic implant abutments were fabricated using alumina, a ceramic with exceptional strength. Alumina, within the realm of ceramics, has advantageous physical qualities. Its bending strength is 547 MPa, while the fracture toughness is 3.55 MPa. The early abutments were customised to conform to the anatomical locations. Alumina abutments showed significant fracture resistance in in vitro experiments (Andersson et al., 1998; Buser et al., 1997; H, 1996; McGlumphy EA, 1992; Prestipino & Ingber, 1993a, 1993b). Nevertheless, clinical investigations revealed that abutment fractures occurred more in single implant restoration (7%) than implant-supported fixed dental prostheses (1.9%). It was too curbed to use anymore (Andersson et al., 2003; Andersson et al., 2001).

(c) ***Zirconia***

Bioceramics has significantly advanced in the field of dental implantology. Yttria-stabilized tetragonal zirconia (Y-TZP) is becoming increasingly popular as both a prosthesis and a dental implant among various bioceramics. There are two distinct types of Y-TZP ceramics: monolithic, which is a one-piece design for the implant and abutment, and two independent components, which are individual parts with a metallic insert that is internally connected. The transformation induced by stress strengthens the toughness of zirconia. A crack is caused by an external force. There is a transition phase from tetragonal to monoclinic due to the stress concentration at the crack's tip. As a result, volume growth increased by 4%. The volume growth creates compressive stress, which leads to crack closure and an improvement in the material's fracture toughness (Camposilvan et al., 2018; Chevalier, 2006; Cruz et al., 2022; Gökçe et al., 2020; Lin & Duh, 2003; Mohan et al., 2007; Piconi & Maccauro, 1999; Sevilla et al., 2009; Variola et al., 2014; Variola, 2009; Wenz et al., 2008; Yılmaz et al., 2017). It also presents corrosion resistance, improved wear resistance, and outstanding aesthetic properties. The fracture toughness and bending strength of zirconia are nearly double those of alumina ceramic, which are 9 MPa and 900 MPa, respectively. According to the in vitro study, zirconia abutments could withstand loads as high as 738 N which is higher than the average occlusal forces 110N that occur naturally in the anterior teeth and 370 N for implants (Filser F, 1997; H, 1996; Haraldson et al., 1979; Paphangkorakit & Osborn, 1997; W, 1989; Yildirim et al., 2003). The setbacks of zirconia abutments, on the other hand, are susceptible to aging and decreasing in physical characteristics. Studart et al. found that the fracture toughness of zirconia is weakened to half (50%) after ten years of artificial ageing in an aqueous environment. Several prosthetic complications related to the zirconia abutments were reported, such as fractures of the abutment and porcelain, abutment screw loosening, and loss of retention. A further 12-year retrospective investigation into zirconia problems revealed the frequent occurrence of abutment fractures at the screw access hole and the implant neck (Studart et al., 2007; Torabinejad et al., 2007). When an implant-supported restoration is subjected to occlusal force, the region around the abutment screw head withstands the most torque and stress, according to studies. This area is also the most crucial for preserving the stability of ceramic abutments (Att et al., 2006; Tripodakis et al., 1995; Yildirim et al., 2003). On the other hand, there have been reports of technical issues about abutment fractures occurring more often with zirconia abutments than with metal abutments. The primary cause of ceramic abutment fractures in many in vitro tests was the development of high tensile pressures in this specific area during function. The brittleness of zirconia causes it to not resist the tension. The excessive tension caused the zirconia abutment to fracture first, prior to the abutment screw (Apicella et al., 2011; Att et al., 2006; Naveau et al., 2019; Pjetursson, Zarauz, et al., 2018; Tripodakis et al., 1995; Yildirim et al., 2003). A recent systematic review compared the clinical outcomes of different types of materials for implant abutments in the anterior crowns. The results revealed that 6 out of 14 studies demonstrated 3–14% fracture rates for ceramic abutments and 0% fracture in the metallic abutments (Totou et al., 2021) . An additional issue of concern is the adhesion between the resin cement and the zirconia substance. Several writers have proposed that a satisfactory and durable connection with zirconia can be achieved by using a composite resin cement that contains 10-methacryloyloxydecyl dihydrogen phosphate (MDP). It has been suggested to prepare the zirconia surfaces by using mechanical or mechanochemical conditioning before treatment (Kern & Wegner, 1998; Özcan & Bernasconi, 2015; Wegner & Kern, 2000). Nevertheless, the brittleness of ceramics also makes them inferior in toughness compared to commercially pure titanium (Camposilvan et al., 2018; Chevalier, 2006; Lin & Duh, 2003; Mohan et al., 2007; Piconi & Maccauro, 1999; Sevilla et al., 2009) .

Zirconia abutments are classified into two types: two-piece abutments with a titanium base in the connecting part and one-piece abutments comprised entirely of zirconia (Chun et al., 2015).

i One-piece Zirconia Abutment

One-piece zirconia abutments are fabricated from monoblocks without a titanium base. There were several complications reported in one-piece zirconia abutment including the titanium implant interface broke down more quickly because of too much wear from continuous loading. Besides, screw head fracture or abutment fracture at the screw head level observed in the study conducted by Alsahhaf et al. and supported by evidence-based data. This showed the head of screw was the most vulnerable area to fracture in all-ceramic abutments (Alsahhaf et al., 2017; Att et al., 2006; Papavasiliou et al., 1996; Stimmelmayr et al., 2012; Strub & Gerds, 2003; Tripodakis et al., 1995; Yildirim et al., 2003). There were also studies demonstrating implant-abutment connection or transmucosal part of abutment were the common fracture point in one-piece zirconia abutment. One-piece zirconia abutments exhibit inferior clinical and technical performance compared to two-piece zirconia abutments, especially in the anterior aesthetic zone. Another limitation of one-piece zirconia abutments is their propensity for fracture, which happens either at the implant-abutment connection or within the transmucosal region of the abutment (Elsayed et al., 2017; Lv et al., 2023). In addition, the use of heterogeneous materials in the connection increases the stress concentration, screw loosening, and permanent damage to the implant geometry, especially when the restoration vertical height is more than 14mm (Brodbeck, 2003; Fabbri et al., 2017; Stimmelmayr et al., 2012).

ii Two-piece Zirconia Abutment

Two-piece zirconia abutments consist of a zirconia component and a titanium base abutment connected to the implant through screw fixation. They have improved esthetics, optimal biological response, and superior mechanical properties, with no adverse effects on the implant–abutment interface (Chun et al., 2015).

Stimmelmayr et al. found that two-piece zirconia abutments connected to a titanium implant exhibited greater fracture resistance than one-piece zirconia abutments. This design overcame the limitation of material heterogeneity and stress concentration in one-piece zirconia abutment while maintaining the benefit of zirconia abutment. The introduction of titanium base abutments improved the fracture resistance and shear force resistance of the abutments (Edelhoff et al., 2019; Sailer et al., 2018; Stimmelmayr et al., 2013).

There were studies exhibited greater fracture strength in two-piece zirconia abutments with internal connections as opposed to zirconia abutments and one-piece zirconia abutments with external connections. However, they found that two-piece zirconia abutments with internal connections tend to fracture before the metal component fractured. The fracture point of zirconia abutments with external connections was seen to be above the implant shoulder, and the fracture point of a one-piece zirconia abutment with internal connections was seen to be beyond the implant shoulder (Mühlemann et al., 2014; Sailer, Sailer, et al., 2009; Truninger et al., 2012).

(d) ***Polyetheretherketone (PEEK)***

Polymeric compounds, such as polyetheretherketone (PEEK), have emerged as new biomaterials in dental implantology since 1987. Abutments, healing caps, and frameworks for implant-supported prostheses have all begun to utilise PEEK in recent years. PEEK is a biphasic semicrystalline polymer with exceptional performance. Its low modulus of elasticity, ranging from 3 to 4 GPa, is similar to that of human bone tissue (14 GPa). PEEK has several desirable properties, including high mechanical strength, low stress shielding, colour stability, resistance to corrosion, and stability in both heat and chemicals. PEEK has a clinical advantage in that it is suitable for making provisional and healing abutments to achieve a well-formed emergence profile (Chokaree et al., 2024; Elsawy et al., 2022; Eschbach, 2000; He et al., 2021; Katzer et al., 2002; Luo et al., 2023; Najeeb et al., 2016; Skinner, 1988; Zhang et al., 2022). Studies also showed that titanium-reinforced PEEK could be more effective in minimising the risk of crestal bone loss and preserving soft tissue stability than conventional titanium abutments. However, research has demonstrated that PEEK abutments can cause an adverse response in soft tissues that is on par with titanium and zirconia. Although, they have been recommended as a viable and aesthetically pleasing choice for both removable and fixed dental prostheses (Enkling et al., 2022; Khurshid et al., 2022; Maté Sánchez de Val et al., 2016). There have been significant concerns regarding the presence of microbial contamination and the colonisation of oral biofilm on PEEK surfaces. Peri-implantitis and peri-implant mucositis may result from bacterial aggregation on a dental implant. Over 40% of implants have been influenced by peri-implantitis, while approximately 22% are afflicted by peri-implant mucositis (Berglundh et al., 2018; Salvi et al., 2017; Zhang et al., 2022). A long-term clinical trial found that PEEK and zirconia abutments had similar plaque accumulation. Conversely, a comprehensive review indicated that PEEK dental prosthesis frameworks had decreased plaque accumulation compared to metal frameworks. Nevertheless, laboratory experiments showed conflicting findings about the buildup of microorganisms on the surface of PEEK, depending on the specific bacterial species. Streptococcus oralis bacteria have been shown to adhere and accumulate on PEEK surfaces at a relatively lower rate than titanium surfaces. When compared to titanium, PEEK shows considerably fewer levels of Enterococcus faecalis, along with greater adherence to Streptococcus mutans and Escherichia coli. According to prior research, attaining strong adhesion with PEEK is challenging owing to its hydrophobic characteristics and low surface energy (Ayyadanveettil et al., 2022; D'Ercole et al., 2020; Escobar et al., 2020; Gama et al., 2024; Sarfraz et al., 2022). In an effort to enhance the adhesion properties of PEEK, a variety of protocols have been looked into. It has been reported that surface modifications such as sandblasting, acid etching, and plasma treatment are efficacious (Stawarczyk et al., 2014; Zhou et al., 2014) . However, the adhesive properties of the 3D-printed PEEK material are not well understood.

2.5 Complications of Implant-Supported Prosthesis

Despite the excellent success rate of dental implants, numerous issues were commonly encountered. In the late 1990s, there were an abundance of issues and shortcomings with dental implants and prostheses that were supported by implants. There are three major categories of dental implant complications: mechanical, biological, and aesthetic (Büyük et al., 2022; Chen et al., 2023; Geng et al., 2004; Goodacre et al., 1999; Koka et al., 2023; Menacho-Mendoza et al., 2022; Monje et al., 2023; Verma et al., 2023; Yi et al., 2018). A group, led by Lang, developed a consensus statement to define the following terms: (Lang et al., 2004)

- The survival of an implant or prosthesis is the treatment outcome assessed during the review; however, its specific status is not mentioned. The success of the implant or prosthesis is considered when there are no issues reported at the follow-up examination.
- The loss of the implant or prosthesis signifies that they were no longer present during the follow-up examination.
- Complications denote that chairside procedures will require additional time following the prosthesis's insertion.
- A follow-up examination reveals a problem or that the implant or prosthesis is absent, indicating failure.

2.5.1 Mechanical Complications

There are three types of mechanical complications. Firstly, the complication pertains to implants, namely implant fractures. Furthermore, it deals with technical problems corresponding to connections, such as the loosening of screws in the prosthesis and abutment, fractures in screws, and abutments. Besides that, it's important to think about problems with the superstructure. These can include cracks in the metal framework, wear and tear on the materials, fractures in the denture base of implant-supported and retained overdentures, chipping off or fractures in the facial and occlusal parts of porcelain veneers, failure of cement, breakdown of prosthetic materials, having to replace prostheses because of complications, fractures in opposing prostheses, and issues with mechanical retention with overdenture parts like bar or clip attachments (Goodacre et al., 1999; Lang et al., 2004; Sailer et al., 2022) .

Screw and abutment loosening are the most frequently encountered mechanical issues. These problems may arise from not-well-designed dental prostheses, excessive force from the muscles of mastication, and overloading force on the teeth. Overall, the incidence rate of prosthetic complications occurring in the first five years was reported to increase from 5.1% to 13%. In comparison, the incidence rate of ceramic chipping was more frequent than screw loosening, which was 11.6% and 4.1%, respectively. According to a meta-analysis undertaken by Pjetursson et al., only 61% of prosthetic implant restorations had no mechanical challenges that arose. In a 12-year follow-up study by Kourtis et al.: the overall incidence rate of prosthetic complications was reported to be less than 10%, or about 9.52% (Albrektsson & Donos, 2012; Jeong et al., 2017; Jung et al., 2008; Jung et al., 2012; Kim et al., 2022; Kourtis et al., 2004; Pjetursson et al., 2007; Sadid-Zadeh et al., 2015; Sailer et al., 2012; Schwarz, 2000; Zembic et al., 2014). The different types of prosthetic complications, including frequency and percentages, are reported in Table 2.1.

The study conducted by Kourtis et al. identified several potential factors that can influence the occurrence of mechanical complications. These factors include the mechanism of the implant-abutment connection (IAC), whether the abutments are screw-retained or cement-retained, the materials used for the implant abutments, the presence of anti-rotational features, the materials and designs of prosthetic restorations, and parafunctional habits (Kourtis et al., 2017).

There are also studies that showed that mechanical complications could possibly be attributed to improper implant design, excessive stresses, and inappropriate occlusion. Nevertheless, they can be mitigated by implementing a design that is optimised and reduces stress distribution. The stress concentration around the implant system, which is a result of continuous masticatory stresses, is substantially correlated with implant component breakage. Stress concentration occurs, especially when there are changes in the cross-sectional area or irregularities in the shape of an implant. This weakens the implant system's ability to withstand the masticatory load, ultimately resulting in the implant's biomechanical failure without proprioceptors, unlike in natural teeth. Design of implants and abutments, types of loads, material of restorations, surface texture, bone density, and implant-bone interaction are some of the biomechanical aspects that impact the distribution of stress around implants. Overloading can transmit stress directly from the implant to the bone, which could cause bone destruction (Altıparmak et al., 2023; Geramizadeh et al., 2017; Kayabasi et al., 2006; Li & Dong, 2017; Tiossi et al., 2012). As a result, the longevity of dental implants is significantly influenced by the implant's shape and material, as well as the optimisation of biomechanical factors to ensure that stress is evenly transferred from the implant to the bone.

Table 2.1: Incidence of Different Types of Prosthetic Complications in 405 Patients in Four Independent Private Dental Offices with Placement of 1692 Dental Implants From January 1991 to December 2002

Complications	Frequency	Percentage
Screw loosening	51	33.55
Screw fracture	20	13.16
Abutment fracture	8	5.26
Cement dissolution-detachment	38	25.99
Restoration chipping	31	20.39
Bar fracture	4	2.63
Total	152	100
Total prosthetic complications 9.52%		

(Kourtis et al., 2004)

2.5.2 Biological Complications

Biologically related implant failure can be categorised into two distinct types: (1) early failure, occurring within the first year or before loading, when osseointegration could not happen, and (2) late failure, occurring after loading and successful osseointegration, which can lead to peri-implant diseases such as peri-implant mucositis, peri-implantitis, and dehiscence (Carr et al., 2019; Schwarz & Ramanauskaite, 2022) . In particular, there are a number of surgical complications that may result in early implant failure. These include bone overheating during implant placement, which can cause bone damage and necrosis; implant impingement on major anatomical structures such as the maxillary sinus membrane, nerves, a natural tooth, or another implant; alterations in neurosensory function; haematoma; and mandible fracture. Not only that, inadequate primary stability owing to low-quality bone or over-countersinking, inappropriate surgical procedures, medically compromised patients, implant surface contamination, and early implant loading are other possible factors in early implant failure (Goodacre et al., 1999; Strasding et al., 2023). In addition, there are several factors responsible for the late failure of dental implants. Possible causes of late failure of dental implants include inflammatory reactions caused by bacteria, occlusal overloading, parafunctional habits such as bruxism, a lack of keratinized mucosa around the implant, exposed threads from implant placement errors, residual titanium particles, adjacent pathology, poor plaque control, poor maintenance, and inadequate removal of dental cement (Koka et al., 2023; Papaspyridakos et al., 2018; Schwarz & Ramanauskaite, 2022) . Peri-implant mucositis and peri-implantitis are the primary root causes of late implant failures. Their distinguishing difference is the involvement of bone loss surrounding an osseointegrated implant in the latter, despite both referring to a specific area of tissue inflammation (Heitz-Mayfield & Salvi, 2018; Schwarz et al., 2018).

Furthermore, there was a discussion about biological concerns that arise due to the existence of a microgap at the IAC. The microgap may arise from factors such as the implant and abutment's shape and materials, the various types of implant-abutment connection, the tightening torque value, and the marginal fit of the implant components. There is a hypothesis that suggests that microleakage could lead to the growth of bacteria in the IAC, which could contribute to peri-implant mucositis and peri-implantitis (Aloise et al., 2010; Broggini et al., 2003; Canullo et al., 2015; Jansen et al., 1997; Rismanchian et al., 2012; Weng et al., 2011). This is because bacteria moving in and out of the implant-abutment interface creates a pumping effect while the implant is working. This causes swelling and tissue loss around the implant. On average, 43% of patients had peri-implant mucositis, whereas 22% suffered peri-implantitis (Derks & Tomasi, 2015).

2.6 Finite Element Analysis (FEA)

FEA is an essential computational tool to predict the mechanical properties of materials with different complex geometries and shapes under different loadings. It also provides reliable data regarding stress distribution and strain deformation in implant components and around the bone tissues (Babaei et al., 2022; Hosseini-Faradonbeh & Katoozian, 2022; Lisiak-Myszke et al., 2020; Poiate et al., 2011) . The strain development in the bone is influenced by the bearing capacity of dental implants, which is in turn determined by the design and material of the superstructures. One approach that has been devised to enhance the uniform distribution of stresses around dental implants involves the implementation of shock-absorbing materials, such as microfilled polymers and acrylic, to mitigate the occlusal forces. The efficacy of finite element (FE) modelling in analysing the mechanical characteristics of dental implants with a variety of prosthetic designs has been demonstrated. Comparative studies on the shock absorption properties of various veneering materials revealed that the use of more rigid materials resulted in greater stress transmission to the fixture, accompanied by a shorter duration of force rise. On the other hand, materials that are more durable experience a longer rising time and lower stress levels (Ciftçi & Canay, 2001; Gracis et al., 1991; Skalak, 1983; Soumeire & Dejou, 1999; van Rossen et al., 1990) . Over the past few decades, dentistry has seen an upward trend in the use of FEA. It is now generally recognised as an accurate means for determining stress distribution and strain deformation in bone, different components of implants, and prostheses. FEA is cost-effective because it enables the use of sophisticated body structures with multiple adjustable test settings. It is also less laborious. In clinical settings, these data may not be readily accessible; however, they are useful for identifying possible challenges and devising effective solutions (Babaei et al., 2022; Hasan et al., 2012; Jemaa et al., 2023a; Lisiak-Myszke et al., 2020; Nisar, 2018).

2.7 Novelty

The transmission of occlusal force to the implant bone interface is influenced by the composition of the implant restorative complex, which includes elements such as the crown, cement layer, and abutment, as well as the direction of loading, potentially compromising the success of implant (Sahoo et al., 2024; Sevimay, Usumez, et al., 2005; Talreja et al., 2023; Wang et al., 2002; Zieliński et al., 2024). Controlling the stress within the implant and its components can avoid possible mechanical and biological complications. The selection of an appropriate restorative material is significant due to the potential implications of restorative materials on the bone's structure and the surrounding soft tissues, according to certain research studies (AlJasser et al., 2021; Coray et al., 2016; Iranmanesh et al., 2014; Pjetursson, Valente, et al., 2018; Rabel et al., 2018; Sadid-Zadeh et al., 2015; Stimmelmayr et al., 2017). The combination of a resilient material in the form of resin with outstanding fracture resistance and tensile strength as well as desirable physical characteristics, especially strength and durability, of ceramics could overcome the limitations of traditional abutment rigidity and minimise the micromovement between the abutment and implant platform, thereby reducing biological and mechanical complications (Hermann et al., 2001; King et al., 2002) .

To the best of the researchers' knowledge, there are no studies investigating the stress distribution of 3D printed ceramic filled hybrid materials and CAD/CAM zirconia as CAD/CAM custom abutments and implant-supported crowns at the various interfaces of implant supported prosthesis: crown, cement between crown and CAD/CAM custom abutment, CAD/CAM custom abutment, abutment screw, cement between CAD/CAM custom abutment and Ti-base abutment, Ti-base abutment and fixture as well as at the peri-implant bone region. Thus, this study aims to address the existing knowledge gap regarding the long-term stability and clinical success of a combination of 3D printed and CAD/CAM polycrystalline ceramic materials for dental implant restorations.

CHAPTER 3: MATERIALS AND METHOD

The following tooth model, different abutment and implant-supported crown materials, components of implants, resin cement, mandible were simulated using the following computer specifications and FEA software. The materials and methods used were shown in Table 3.1. The dimensions in x-axis, y-axis and z-axis of components of implant and bone structure in CAD were shown in Table 3.2.

3.1 Materials and Methods

Table 3.1:Materials And Methods Used

Materials	Methods
Simulated mandibular first molar implant supported crown • CAD/CAM Zirconia • 3D printed VarseoSmile® Crown Plus • 3D printed VarseoSmile®TriniQ®	CAD
Simulated CAD/CAM custom abutment	CAD
Simulated cement layer (50μm)	CAD
Simulated Ti-base abutment, abutment screw, fixture,	Stereolithography format (STL) provided by manufacturer

Table 3.2: Dimension of Components of Implant and Bone Structure CAD

	X-axis (mm)	Y-axis (mm)	Z-axis (mm)
Crown	8.5	6.5	9.5
Cement between crown & CAD/CAM custom abutment	6.5	3.5	6.5
CAD/CAM custom abutment	7.0	6.0	7.5
Cement between CAD/CAM custom abutment & Ti-base abutment	3.5	4.5	3.5
Ti-base abutment	4.2	7.0	4.2
Abutment screw	2.4	7.6	2.4
Fixture	4.1	11.5	4.1
Mandibular bone	23.0	17.0	22.0
Cancellous bone	21.0	15.0	22.0

3.2 Computer Specification

Computer specification for FEA simulation in this study was stated as per table below. (Table 3.3)

Table 3.3: Computer Specification

Model	PC - Desktop
Processor	Intel(R) Core (TM) i3-10105F CPU @ 3.70GHz (4 cores/8 logical processor)
Graphics Card	NVIDIA GTX 1660
RAM	16GB DDR4 3200 MHz
Hard Disk	2 TB SSD
OS	Windows 11

3.3 Software

Commercially available software for geometry preparation and FEA were stated as table below. (Table 3.4)

Table 3.4: FEA Software

CAD and Geometry clean-up	ANSYS Space Claim
Finite Element Analysis	ANSYS Workbench 2021 R1

3.4 Overview Process of FEA

The FEA process was divided to 3 major processes. They were pre-processing, processing and post-processing. (Figure 3.1 & 3.2)

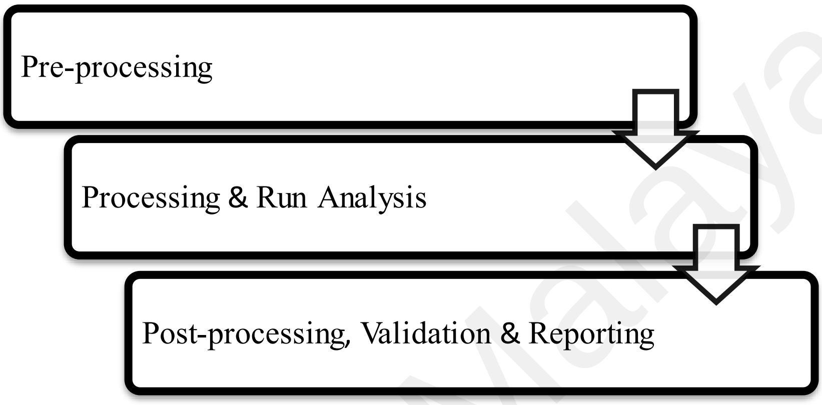


Figure 3.1: The Overall Process of FEA

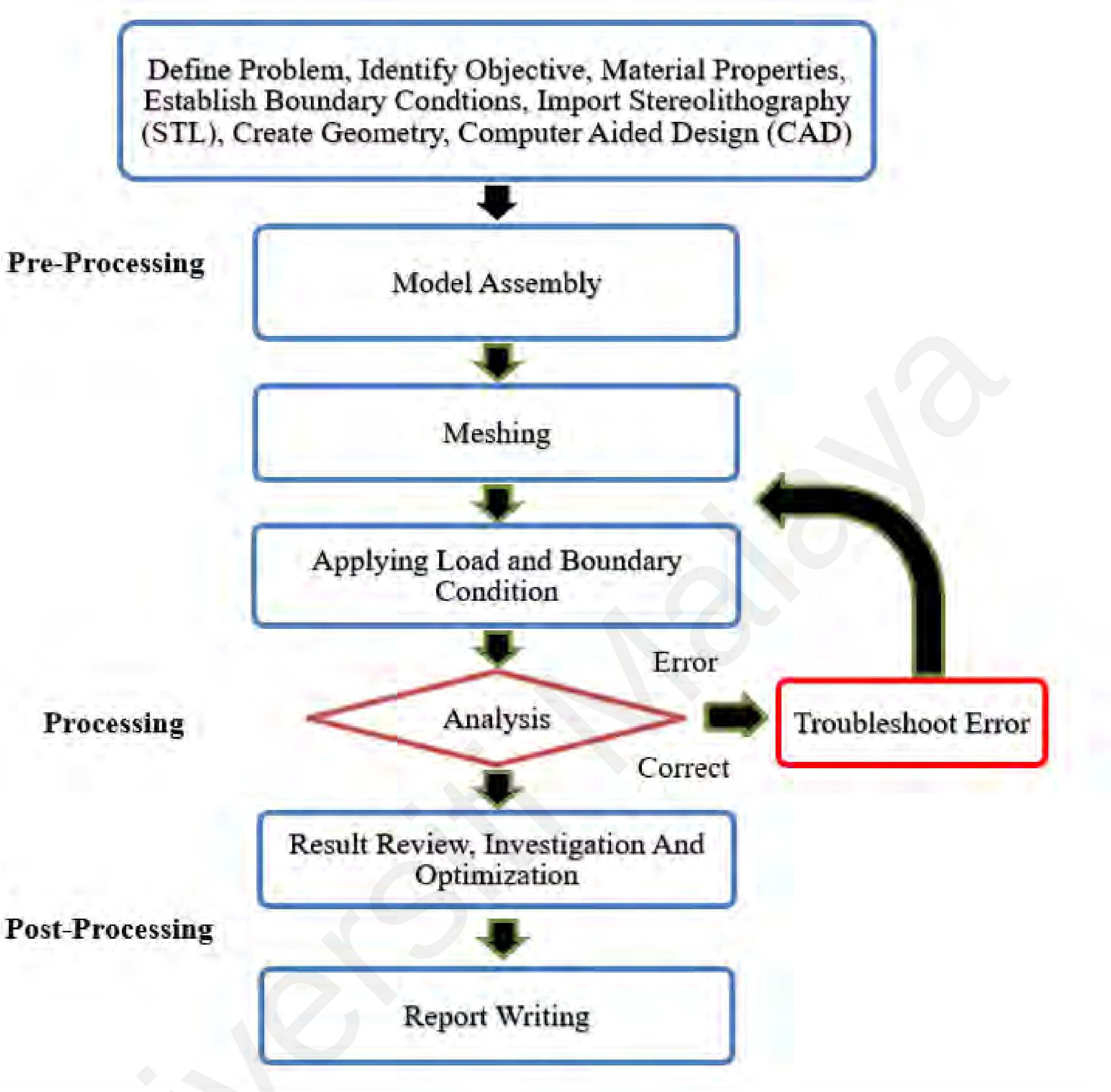


Figure 3.2: The Flow for the FEA Process in Details

3.5 Pre-Processing: Import STL

3.5.1 The Model

A 3D finite element model comprising of crown, cement between crown and CAD/CAM custom abutment, CAD/CAM custom abutment, cement between CAD/CAM custom abutment and Ti-base abutment, abutment screw, Ti-base abutment, fixture, cortical and cancellous bone was prepared to evaluate the von Mises stresses at each component. All the components were imported individually from STL. These formats were common files used for 3D modeling, especially 3D printing, 3D scanning, rapid prototyping and computer-aided design and CAD/CAM. It represented the surface geometry of a 3D object without any representation of colour, texture or other common CAD model attributes. In a simpler explanation, it transformed the surface into a kind of mesh of triangles by approximating surfaces of the object.

3.5.1.1 The Crown

The crown model was designed as a mandibular first molar crown using CAD software and exported in STL. The CAD software used was Blenderfordental®. The crown was designed to provide minimal thickness of 1mm. The marginal thickness and occlusal thickness were 1 mm. The buccolingual width was 8.5mm, occluso-cervical height was 6.5 mm, mesiodistal length was 9.5 mm (Yoon et al., 2018).

3.5.1.2 The CAD/CAM Custom Abutment

The CAD/CAM custom abutment was also known as the mesostructure of the crown, connecting between the crown and titanium base abutment. The CAD software, Blenderfordental ® was used to design the model in STL format. The abutment designed to provide minimal thickness and a marginal line width of 1mm.

3.5.1.3 The Abutment Screw

The STL file was provided by the manufacturer, BEGO Implant Systems GmbH & Co. The height of the abutment screw was 7.6 mm and made of Ti-6Al-4V according to ASTM F-136.

3.5.1.4 The Ti-Base Abutment

The STL of Ti-base abutment (Bego PS TiB GH 1.5 RSX 4.1) was provided by the manufacturer, BEGO Implant Systems GmbH & Co. It was recommended by manufacturer for the fixture of mandibular first molar with diameter 4.1mm. The transgingival height was selected to be 1.5mm, as it is the most commonly used height for abutments.

3.5.1.5 The Fixture

The bone level implant BEGO Semados® RSXPro measured diameter 4.1mm x height 11.5mm was used. Its STL file was provided by the manufacturer, BEGO Implant Systems GmbH & Co.

3.5.1.6 The Mandible

A Type II bone structure that represented the section of mandibular first molar region (X-axis: 23mm; Y-axis:17mm; Z-axis: 22mm) with average thickness of at least 17mm for each axis according to the classification system by Lekholm and Zarb (Lekholm, 1985). It consisted of 2 layers which were cortical bone of thickness 2 mm (Sevimay, Usumez, et al., 2005). The 3D model of the dental implant was submerged in the bone structure assuming 100% osseointegration. Assuming that the gingiva was negligible in the model. The Ti-base abutment was perfectly fit into the fixture.

3.5.1.7 The Cement

3M™ RelyX™ U200 Self-Adhesive Resin Cement 50µm in thickness was placed between the crown and abutment as well as between abutment screw and Ti-base abutment to simulate the real clinical scenario. The cement layer was 50µm (Bagheri, 2013; Kaleli et al., 2017; Kious et al., 2009; Wu & Wilson, 1994).

3.5.2 The Geometry of Assembled Model

All the components were assembled to form the model as shown in the figure after every component was set up.

3.6 Pre-Processing: Geometry Checking, Simplification, Rebuilding and Cleaning Up

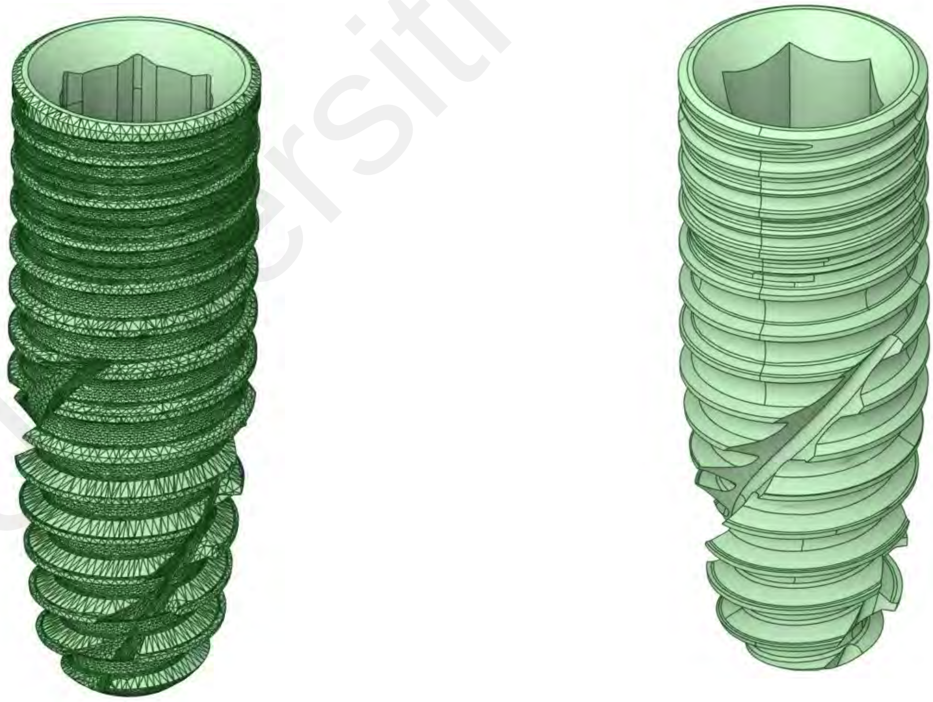
The STL were required to be converted into the Standard for the Exchange of Product (STP/STEP) which was a file extension for 3D graphic file used by CAD software. It was used to store and transfer 3D and two-dimensional (2D) geometry models, parts and design data. STP provides more detailed information compared to the STL format. It allowed for high dimensional accuracy and smoother curves. It was also cross platform compatible and easier to edit. The converted file had a very large file size hence would impact the analysis time. Thus, the components would require to be rebuilt or simplified. The simplified geometry would generate high quality meshes with lesser fault. Simplified models were easier to apply boundary conditions and could reduce computational costs without affecting the precision and accuracy.

To rebuild or simplify, there were few considerations needed to be addressed. Geometry features that give minimal impact to the overall component shape and/or analysis would be neglected and simplified. However, geometries that gave significant impact would be preserved and maintained.

The purpose of cleaning up the geometries was to remove extra edges, points, redundant faces and small edges in order to optimize the mesh with fewer elements and improve computational efficiency in simulations. All the geometry checking, cleaning up, simplification and rebuilding used the Ansys SpaceClaim.

3.6.1 Fixture

The STL of fixture was provided by the manufacturer. The X, Y and Z dimensions were 4.1mm, 11.5mm and 4.1mm respectively. It required great effort to clean up and simplify the geometry of the implant fixture due to its complex thread shape which could not be easily replicated or reconstructed using Ansys SpaceClaim. Since the thread was the critical feature to simulate the implant bone interface, it was crucial to preserve the thread shapes to simulate clinical case conditions. The STL file of fixture was compared before and after cleaned up in Figure 3.3 (A) and 3.3(B).

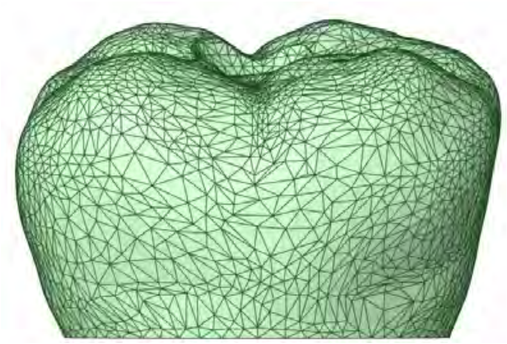


A B

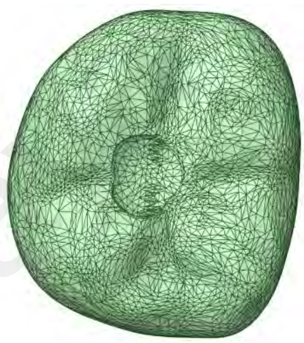
Figure 3.3: Comparison between STL file of Fixture and Cleaned Up Geometry.
(A): Before Cleaned Up
(B): After Cleaned Up

3.6.2 Crown

The crown was designed using the software Blenderfordental® software. The X,Y and Z dimensions were 8.5mm, 6.5mm and 9.5mm respectively. The original crown profile (STL) was compared with the cleaned up geometry in the following figure (Figure 3.4, 3.5 and 3.6)

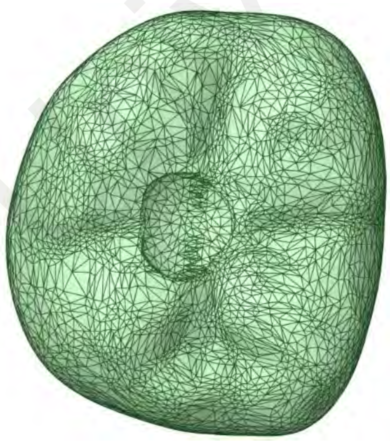


A

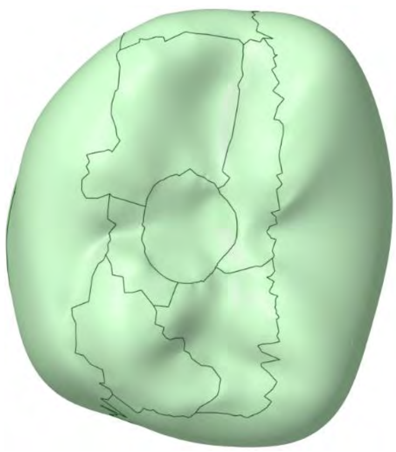


B

Figure 3.4: (A): The Original Crown Profile Buccal View; (B): Occlusal View



A



B

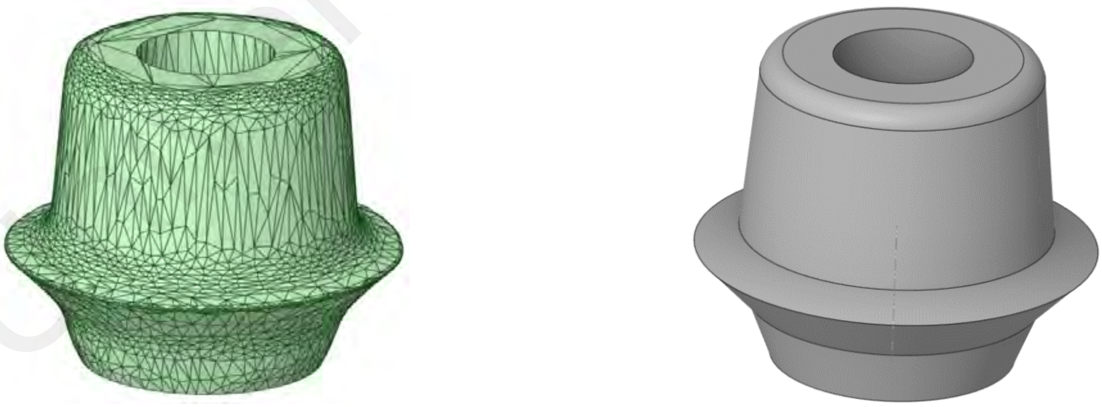
Figure 3.5: Comparison between STL of Crown Profile & After Cleaned Up Geometry.
(A): Original Crown Profile STL: Occlusal View
(B): After Cleaned Up Geometry: Occlusal View

A B

Figure 3.6: Comparison between STL of Crown Profile & After Rebuilt Geometry.
(A): Original Crown Profile STL: Proximal View
(B): After Rebuilt Geometry: Occlusal View

3.6.3 CAD/CAM Custom Abutment

The CAD/CAM custom abutment was rebuilt based on the dimensions measured from STL files obtained from the manufacturers. Its X, Y and Z dimensions were 7.0mm, 6.0mm and 7.5mm respectively. The STL file of CAD/CAM custom abutment was compared before and after rebuilt in Figure 3.7(A) and 3.7(B).



A B

Figure 3.7: Comparison between Original CAD/CAM custom Abutment STL and After Cleaned Up Geometry.
(A): Original Abutment Profile STL
(B): Rebuilt Geometry

3.6.4 Abutment Screw

The screw geometries were rebuilt using the Ansys SpaceClaim. A measurement was taken from the STL file obtained from the manufacturer and rebuilt based on the dimensions taken. The X, Y and Z dimensions were 2.4mm, 7.6mm and 2.4mm respectively. Screw threads were simplified as a simple cylinder at non-contact area as it was not deemed critical features in this study. The comparison between STL files and the rebuilt geometries was shown in Figure 3.8 (A) and 3.8(B).

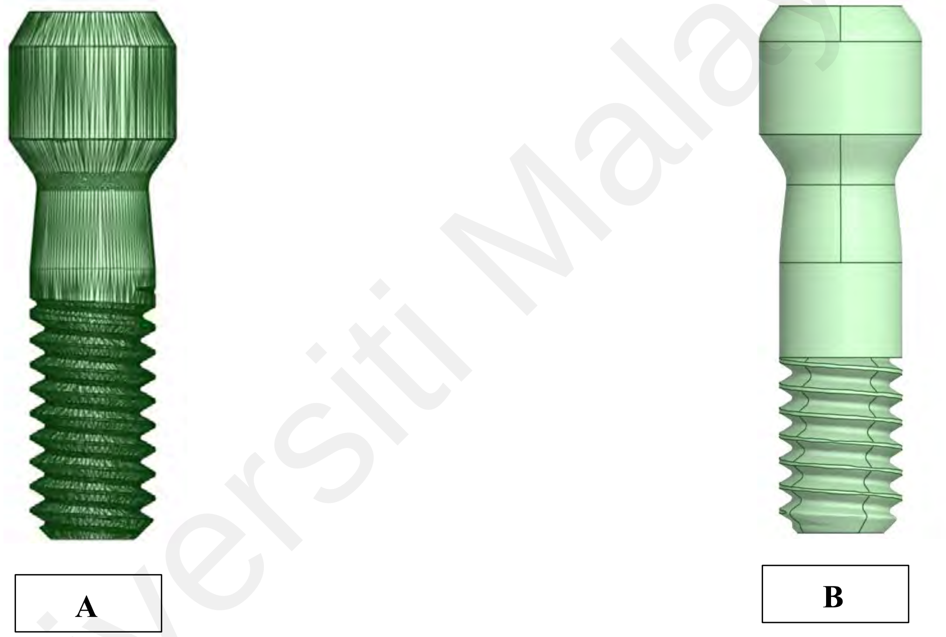
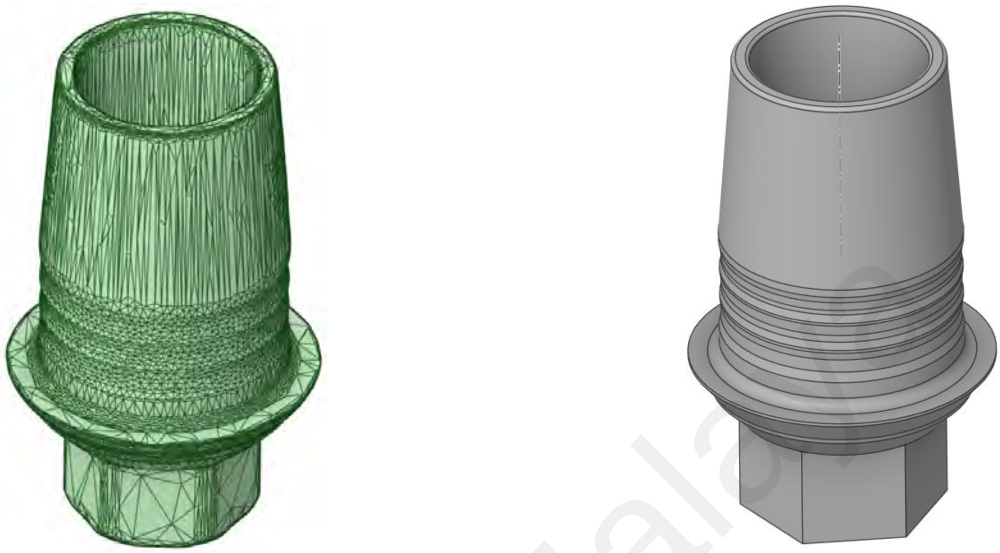


Figure 3.8: Comparison between Original Abutment Screw STL vs Cleaned and Rebuilt Abutment Screw.
(A): Original Abutment Screw STL
(B): Cleaned & Rebuilt Abutment Screw

3.6.5 Ti-base Abutment

The Ti-base abutment geometries were rebuilt using the Ansys SpaceClaim. A measurement had been taken from the STL file obtained from the manufacturer and rebuilt based on the dimensions taken. The X, Y and Z dimensions were 4.2mm, 7.0mm and 4.2mm respectively. The comparison between original titanium base abutment and rebuilt geometries was shown in Figure 3.9 (A) and 3.9 (B).

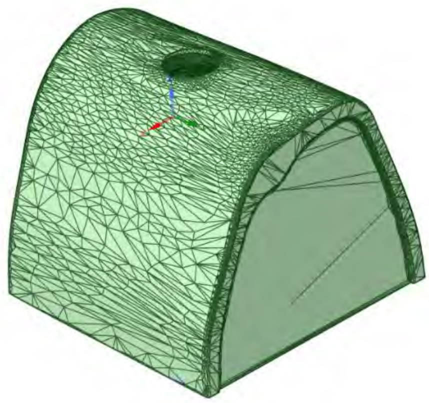


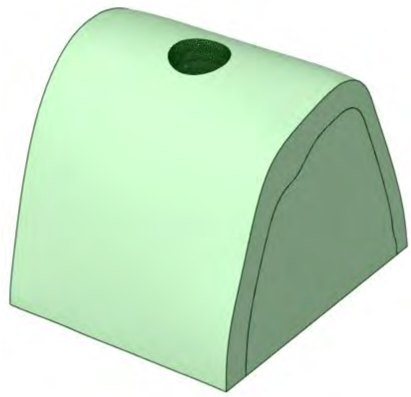
A **B**

Figure 3.9: Comparison between Original Ti-base Abutment & Cleaned and Rebuilt Ti-base Abutment.
(A): Original Ti-base Abutment STL
(B): Cleaned and Rebuilt Ti-baseAbutment

3.6.6 Cortical Bone and Cancellous Bone

The original shape of both cortical and cancellous bones were maintained as per imported in chapter. Minimal change applies in the overall shape and geometrical features of the bones. They were designed using Blenderfordental® software. The X, Y and Z dimensions of mandibular bone were 23.0mm, 17.0mm and 22.0mm respectively whereas the X, Y and Z dimensions of cancellous bone were 21.0mm, 15.0mm and 22.0mm respectively. The STL file of cortical and cancellous bone was compared before and after cleaned up in Figure 3.10 (A) and 3.10 (B)





A B

Figure 3.10: Comparison of Original Cortical and Cancellous Bone and Cleaned Bone Geometry.
(A): Original Cortical and Cancellous Bone STL
(B): Cleaned Geometry Cortical and Cancellous Bone STL

3.7 Pre-Processing:Meshing

After cleaning up and rebuilding, meshing or mesh generation discretized a geometry surface or volume into multiple smaller and simpler elements. The smaller elements formed a mesh which approximated the shape and behaviour of the original domain. For complex geometries, 3D tetrahedron mesh was applied in meshing the components in this analysis. Only titanium base abutment, abutment screw and abutment could be meshed using 3D hexahedral mesh type. The overall meshed assembly for all the components as shown in the following figure. (Figure 3.11)

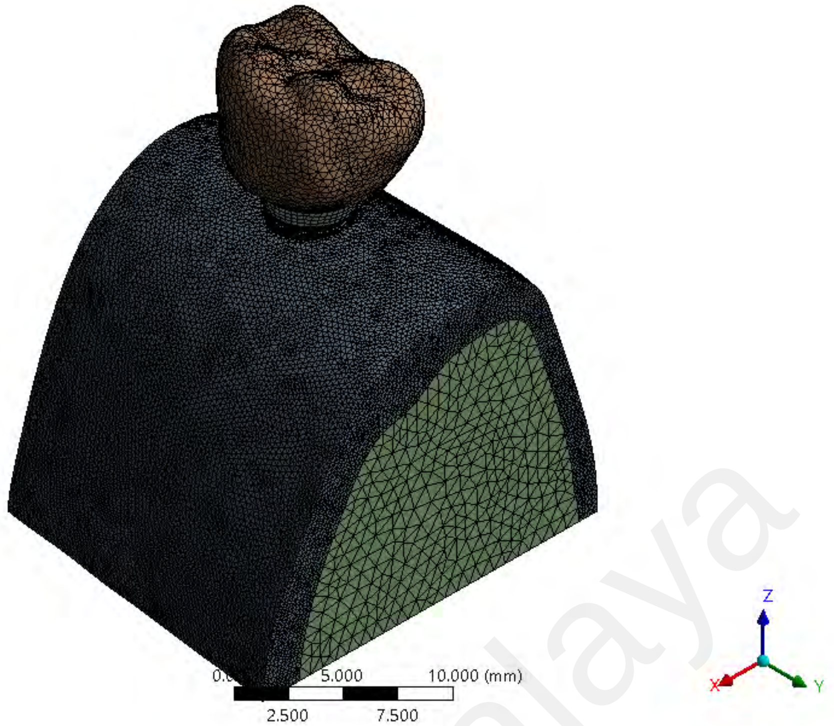


Figure 3.11:Assembled Model of 3D Tetrahedron Mesh for Ansys

The 3D hexahedron mesh was applied because

- All the 3D were comparable in the following figure. (Figure 3.12)

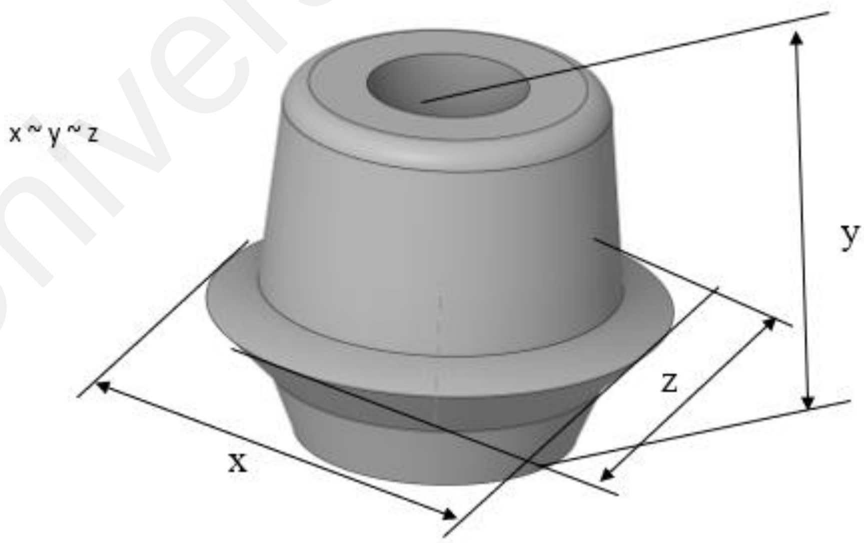


Figure 3.12: The Three Dimension were Comparable

- Complex shape of the crown and implant that made 3D hex mesh almost impossible.

Figure 3.13: Complex and Organic Shape of the Components

3.8 Load and Boundary Condition

3.8.1 Load Case 1: Vertical Load 600N

For Load case 1, a 600N of axial forces were applied to the central axis of the implant onto the crown (Ausiello et al., 2023; Duan & Griggs, 2015; Lin et al., 2020; Tribst et al., 2024) . Figure 3.14 showed the vertical load (600N) was applied and the load application area at each of the crown.

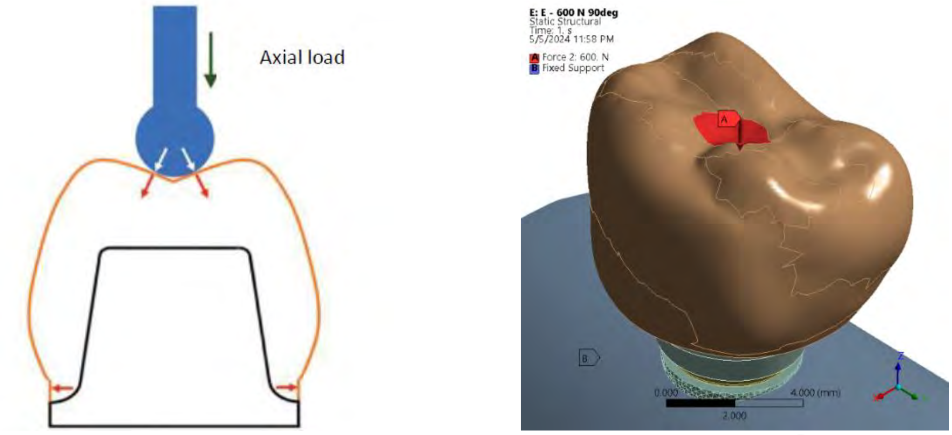


Figure 3.14: Vertical Load 600N was Applied to the Central Axis of Implant onto the Crown.

3.8.2 Load Case 2: Oblique Load 225N

For Load case 2, a 225N oblique forces were applied 45° to the central axis of the implant representing eccentric forces acting on the crown (da Costa Ward et al., 2024; Hariharan et al., 2024) . Figure 3.15 showed oblique load (225N) was applied and the load application area at each of the crown.

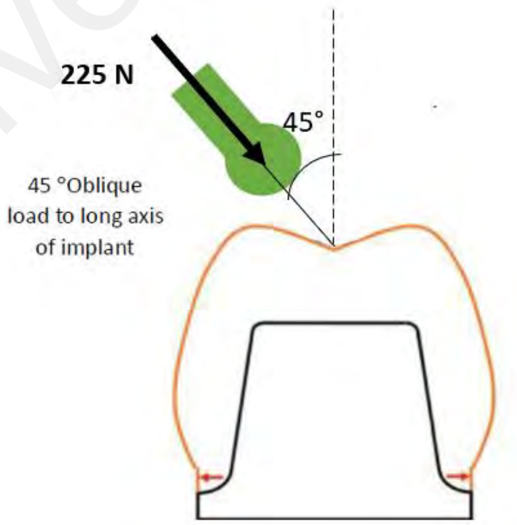


Figure 3.15: Oblique Load 225N was Applied 45° to the Central Axis of Implant onto the Crown

3.9 Material Properties Definition

The mechanical properties of the different restorative materials such as VarseoSmile® Crown Plus, monolithic zirconia, VarseoSmile® TriniQ®, fixture, CAD/CAM zirconia custom abutment, abutment screw, Ti-base abutment, cortical bone, cancellous bone and 3M™ RelyX™ U200 Self-Adhesive Resin Cement were shown in the following table. (Table 3.5)

Table 3.5: Young Modulus and Poisson Ratio of Each Material

Material	Young Modulus (GPa)	Poisson Ratio (v)	References
Cortical Bone	13.7	0.30	(Sevimay, Turhan, et al., 2005)
Cancellous Bone	1.37	0.30	(Sevimay, Turhan, et al., 2005)
Fixture (Titanium)	110	0.35	(Sevimay, Turhan, et al., 2005)
Ti-base Abutment	110	0.35	(Sevimay, Turhan, et al., 2005)
CAD/CAM Zirconia Custom Abutment	210	0.30	(Sannino et al., 2009)
Monolithic Zirconia	210	0.30	(Huang et al., 2024; Juneja et al., 2024)
VarseoSmile® Crown Plus	4.51	0.30	(Ramos Nde et al., 2016)
VarseoSmile® TriniQ®	3.60	0.30	(Ramos Nde et al., 2016)
3M™ RelyX™ U200 Self-Adhesive Resin Cement	6.6	0.33	3M Manufacturer

3.10 Processing: Analysis

The meshed models were transferred to FEA Software (Ansys Workbench 2021 R1) for stress distribution analysis. All the models were considered homogenous, isotropic and linearly elastic. The linear static type of analysis was carried out as it was used to determine the behaviour of structures or components under static loads. The analysis was done with the following assumption:

- Linearity: The material behaviour was linear, meaning that the relationship between stress and strain was proportional.
- Small deformations: The deformations of the structure were small and did not affect the geometry of the components.
- Static loads: The loads applied to the structure were constant and did not change with time.

There were total 5 groups of different combinations of crown and CAD/CAM custom abutment materials analysed in this study shown in the figure below. (Table 3.6)

Table 3.6: 5 Groups of Different Combinations of Crown and CAD/CAM Custom Abutment Materials

Groups	Different Combinations of Crown and CAD/CAM Custom Abutment Materials
ZR-ZR	CAD-CAM zirconia crown cemented to CAD-CAM zirconia custom abutment which was cemented to Ti-base abutment (control group).
VSC-ZR	3D-printed VarseoSmile ®Crown Plus crown cemented to CAD/CAM zirconia custom abutment which was cemented to Ti-base abutment
ZR-VSC	CAD-CAM zirconia crown cemented to 3D-printed VarseoSmile® Crown Plus custom abutment which was cemented to Ti-base abutment
VST-ZR	3D-printed VarseoSmile® TriniQ® crown cemented to CAD/CAM zirconia custom abutment which was cemented to Ti-base abutment
ZR-VST	CAD-CAM zirconia crown cemented to 3D-printed VarseoSmile® TriniQ® custom abutment which was cemented to Ti-base abutment

Group ZR-ZR	Components
	CAD-CAM zirconia crown
	Resin cement RelyX U200
	CAD-CAM zirconia custom abutment
	Resin cement RelyX U200
	Abutment screw
	Ti-base abutment
	Fixture RSX PRO diameter 4.1mm x 11.5mm
	Sectional segment bone

Figure 3.16: Group ZR-ZR: CAD-CAM Zirconia Crown Cemented to CAD-CAM Zirconia Custom Abutment which was Cemented to Ti-base Abutment (Control Group)

Group VSC-ZR:	Components
	3D-printed VarseoSmile® Crown ^{Plus} crown
	Resin cement RelyX U200
	CAD-CAM zirconia custom abutment
	Resin cement RelyX U200
	Abutment screw
	Ti-base abutment
	Fixture RSX PRO diameter 4.1mm x 11.5mm
	Sectional segment bone

Figure 3.17: Group VSC-ZR: 3D-Printed VarseoSmile® Crown ^{Plus} Crown Cemented to CAD-CAM Zirconia Custom Abutment which was Cemented to Ti-base Abutment

Group ZR-VSC:	Components
	CAD CAM zirconia crown
	Resin cement RelyX U200
	3D-printed VarseoSmile® Crown Plus custom abutment
	Resin cement RelyX U200
	Abutment screw
	Ti-base abutment
	Fixture RSX PRO diameter 4.1mm x 11.5mm
	Sectional segment bone

Figure 3.18: Group ZR-VSC: CAD-CAM Zirconia Crown Cemented to 3D-Printed VarseoSmile® Crown Plus Custom Abutment which was Cemented to Ti-base Abutment

Group VST-ZR:	Components
	3D-printed VarseoSmile ® TriniQ® crown
	Resin cement RelyX U200
	CAD-CAM zirconia custom abutment
	Resin cement RelyX U200
	Abutment screw
	Ti-base abutment
	Fixture RSX PRO Diameter 4.1mm x 11.5mm
	Sectional segment bone

Figure 3.19: Group VST-ZR: 3D-Printed VarseoSmile ® TriniQ® Crown Cemented to CAD-CAM Zirconia Custom Abutment which was Cemented to Ti-base Abutment

Group ZR-VST:	Components
	CAD/CAM zirconia crown
	Resin cement RelyX U200
	3D-printed VarseoSmile ® TriniQ® custom abutment
	Resin cement RelyX U200
	Abutment screw
	Ti-base abutment
	Fixture RSX PRO diameter 4.1mm x 11.5mm
	Sectional segment bone

Figure 3.20: Group ZR-VST: CAD-CAM Zirconia Crown Cemented to 3D-Printed VarseoSmile ® TriniQ® Custom Abutment which was Cemented to Ti-base Abutment

CHAPTER 4: RESULTS

4.1 Load Case 1

The result of von Mises stress value at overall the highest stress area, crown, cement between crown and CAD/CAM custom abutment, CAD/CAM custom abutment, abutment screw, cement between abutment screw and Ti-base abutment, Ti-base abutment, fixture, cortical bone and cancellous bone under vertical load (600N) was displayed in the Table 4.1 and Figure 4.1.

The result of von Mises stress percentage difference at overall the highest stress area, crown, cement between crown and CAD/CAM custom abutment, CAD/CAM custom abutment, abutment screw, cement between abutment screw and Ti-base abutment, Ti-base abutment, fixture, cortical bone and cancellous bone under vertical load (600N) compared to control group (Group ZR-ZR) was displayed in the Table 4.2.

Table 4.1: Result of Load Case 1: Comparison of Von Mises Stress Of Overall The Highest Stress Area, Crown, Cement between Crown and CAD/CAM Custom Abutment, CAD/CAM Custom Abutment, Abutment Screw, Cement between CAD/CAM Custom Abutment and Ti-base Abutment, Ti-base Abutment, Fixture, Cortical Bone and Cancellous Bone Among All 5 Groups of FEA Models under Load Case 1.

Group	Von Mises Stress (MPa)				
	ZR-ZR	**VSC-ZR**	**ZR-VSC**	**VST-ZR**	**ZR-VST**
Overall The Highest Stress Area	333.65	330.89	242.02	330.92	247.974
Crown	198.2	173.92	213.9	173.66	214.39
Cement Between Crown & CAD/CAM Custom Abutment	36.39	192.93	28.19	214.57	28.92
CAD/CAM Custom Abutment	266.47	264.92	46.66	265.63	44.62
Abutment Screw	158.68	158.53	157.84	158.52	157.82
Cement Between CAD/CAM Custom Abutment & Ti-base Abutment	20.45	23.23	70.14	23.16	72.52
Ti-base Abutment	333.65	330.89	242.02	330.92	247.97
Fixture	250.95	251.47	203.8	251.49	201.3
Cortical Bone	122.2	122.44	125.19	122.45	125.32
Cancellous Bone	9.38	9.38	9.35	9.38	9.35

ZR-ZR: CAD/CAM zirconia crown- CAD/CAM zirconia custom abutment;
VSC-ZR: 3D Printed VarseoSmile® Crown Plus crown- CAD/CAM zirconia custom abutment;
ZR-VSC: CAD/CAM zirconia crown-3D Printed VarseoSmile® Crown Plus custom abutment;
VST-ZR: 3D Printed VarseoSmile® TriniQ ® crown-CAD/CAM zirconia custom abutment;
ZR-VST: CAD/CAM zirconia crown-3D Printed VarseoSmile® TriniQ® custom abutment

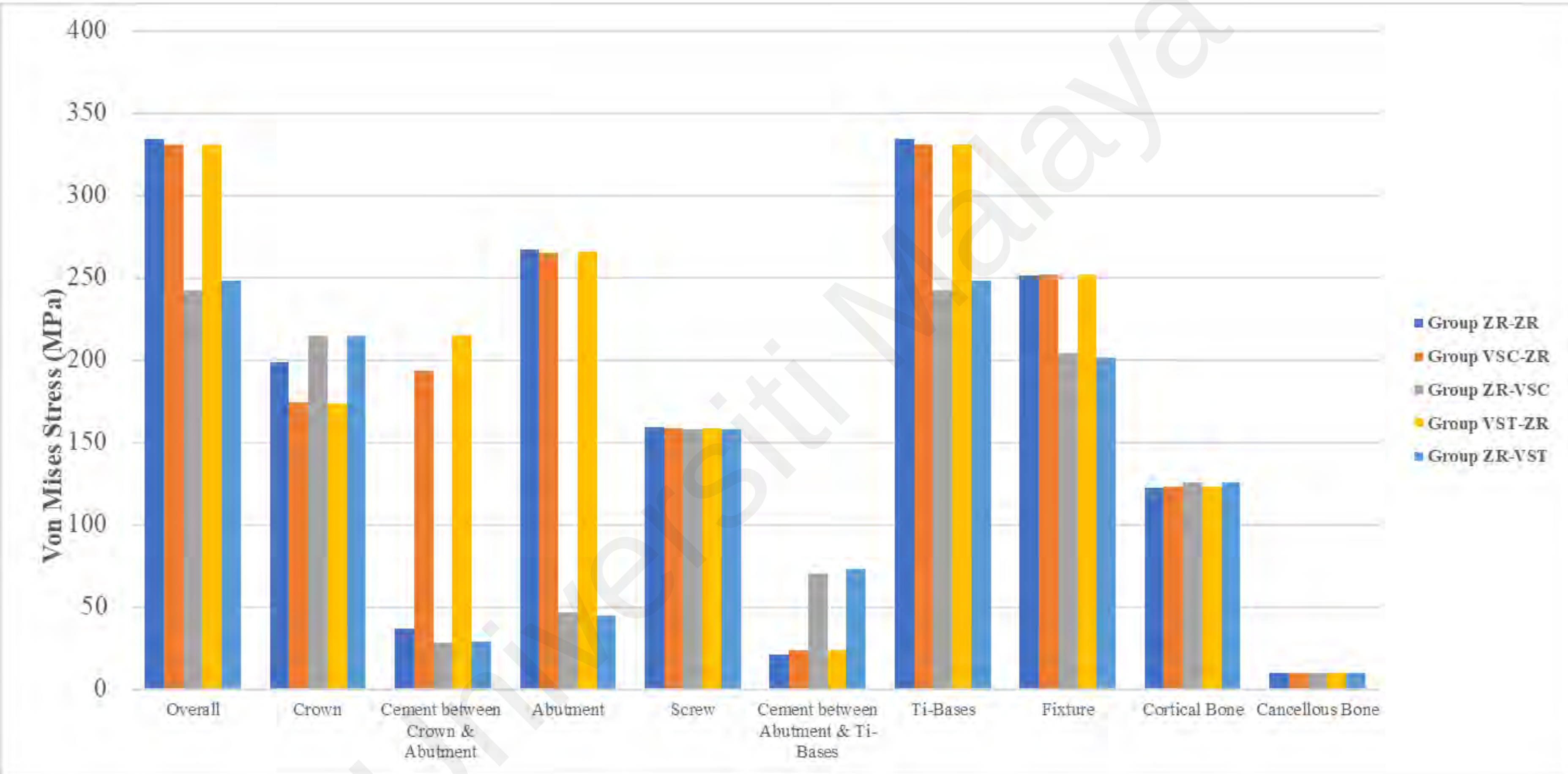


Figure 4.1: Result of Load Case 1: Comparison of Von Mises Stress of Overall The Highest Stress Area, Crown, Cement between Crown and CAD/CAM Custom Abutment, CAD/CAM Custom Abutment, Abutment Screw, Cement between CAD/CAM Custom Abutment and Ti-base Abutment, Ti-base Abutment, Fixture, Cortical Bone, and Cancellous bone among all five group of FEA Models under Load Case 1

Table 4.2: Comparison of the Von Mises Stress Percentage Difference Of the Overall The Highest Stress Area, Crown, Cement between Crown and CAD/CAM Custom Abutment, CAD/CAM Custom Abutment, Abutment Screw, Cement between CAD/CAM Custom Abutment and Ti-base Abutment, Ti-base Abutment, Fixture, Cortical Bone and Cancellous Bone Among All 5 Groups of FEA Models under Load Case 1 Compared to Control Group ZR-ZR

Group	Von Mises Stress Percentage Difference (%)				
	ZR-ZR	VSC-ZR	ZR-VSC	VST-ZR	ZR-VST
Overall The Highest Stress Area	Control	-0.83	-37.86	-0.82	-34.55
Crown	Control	-13.96	7.34	-14.13	7.55
Cement Between Crown & CAD/CAM Custom Abutment	Control	81.14	-29.09	83.04	-25.83
CAD/CAM Custom Abutment	Control	-0.59	-471.09	-0.32	-497.20
Abutment Screw	Control	-0.09	-0.53	-0.10	-0.54
Cement Between CAD/CAM Custom Abutment & Ti-base Abutment	Control	11.97	70.84	11.70	71.80
Ti-base Abutment	Control	-0.83	-37.86	-0.82	-34.55
Fixture	Control	0.21	-23.14	0.21	-24.66
Cortical Bone	Control	0.20	2.39	0.20	2.49
Cancellous Bone	Control	0.00	-0.32	0.00	-0.32

ZR-ZR: CAD/CAM zirconia crown-CAD/CAM zirconia custom abutment;
VSC-ZR: 3D Printed VarseoSmile® Crown Plus crown- CAD/CAM zirconia custom abutment;
ZR-VSC: CAD/CAM zirconia crown-3D Printed VarseoSmile® Crown Plus custom abutment;
VST-ZR: 3D Printed VarseoSmile® TriniQ® crown- CAD/CAM zirconia custom abutment;
ZR-VST: CAD/CAM zirconia crown-3D Printed VarseoSmile® TriniQ® custom abutment

4.1.1 Overall The Highest Stress Area

Overall, the highest von Mises stress was concentrated at the Ti-base abutment among five groups. Group ZR-ZR showed the highest von Mises stress value which was 333.65MPa. On the contrary, Group ZR-VSC showed the lowest von Mises stress value which was 242.02MPa. The von Mises stress in Group ZR-VSC showed the most significant decrease which was 37.86% compared to control group ZR-ZR.

4.1.2 Crown

At the crown level, the von Mises stress among 5 groups were nearly equivalent. Groups ZR-VSC and Group ZR-VST showed slightly higher stress values which were 213.9MPa and 214.39MPa respectively. The VSC-ZR and VST-ZR groups showed nearly the same decline in stress value, hitting nearly to a 15% drop.

4.1.3 Cement between Crown & CAD/CAM Custom Abutment

Groups VSC-ZR and VST-ZR showed higher von Mises stresses, which were 192.93 MPa and 214.57 MPa at the cement layer between the crown and CAD/CAM custom abutment, respectively, compared to the other groups. Group ZR-VSC showed the least stress, which was 28.19 MPa and Group ZR-VST showed the second least stress, which was 28.92MPa. There were around 81% to 83% increases in the von Mises stress values of Groups VSC-ZR and VST-ZR. In this cement layer, the von Mises stress values in Groups ZR-VST and ZR-VSC showed a drop of about 30%.

4.1.4 CAD/CAM Custom Abutment

Among the several groups, Group ZR-VST showed the lowest von Mises stress level at the CAD/CAM custom abutment, measuring 44.62MPa and Group ZR-VSC showed the second least stress which was 46.66MPa. On the other hand, Group ZR-ZR showed the highest stress value, reaching 266.47 MPa. Group ZR-VSC and Group ZR-VST had a significant decrease in von Mises stress at the CAD/CAM custom abutment, with a reduction of five times which was equivalent to the range of 471.09% to 497.20% compared to other groups.

4.1.5 Abutment Screw

The von Mises stress at the abutment screw remains consistent in the range of 157.82MPa to 158.68MPa, irrespective of the various combinations of specific abutment and crown materials. The von Mises stress percentage difference in all five groups was insignificant which was in a range of 0.09% to 0.54%.

4.1.6 Cement between CAD/CAM Custom Abutment and Ti-base Abutment

Groups ZR-VSC and ZR-VST showed a greater von Mises stress value in the cement layer, ranging from 70MPa to 73MPa, in comparison to the other groups. In general, the four groups showed increased level of von Mises stress in the range of 11.70% to 71.80% compared to the control group ZR-ZR.

4.1.7 Ti-base Abutment

Group ZR-VSC and ZR-VST had the lowest von Mises stress levels at the Ti-base abutment, measuring 242.02 MPa and 247.97 MPa, respectively. In contrast, Group ZR-ZR showed the greatest stress level, measuring 333.65 MPa. Both the ZR-VSC and ZR-VST groups showed around a 40% reduction in stress value compared to the control group ZR-ZR.

4.1.8 Fixture

Groups ZR-VSC and ZR-VST showed lower von Mises stress than other groups, at 203.8 MPa and 201.3 MPa, respectively. However, the reduction in stress was moderate in these two groups in accordance to the control group, at roughly 25%.

4.1.9 Cortical Bone and Cancellous Bone

Similarly, in all the models, the von Mises stress in cortical and cancellous bones were comparable among the groups regardless of load application and that was in a range of 122.2 MPa to 125.32 MPa for cortical bone and 9.35 MPa to 9.38 MPa for cancellous bone. Overall, the cortical bone in all groups showed a minimal increase in stress which was 0.20% to 2.39%. In cancellous bone, Groups ZR-VSC and ZR-VST showed a decreased stress of 0.32%.

4.2 Load Case 2

The result of von Mises stress value at overall the highest stress area, crown, cement between crown and CAD/CAM custom abutment, CAD/CAM custom abutment, abutment screw, cement between CAD/CAM custom abutment and Ti-base abutment, Ti-base abutment, fixture, cortical bone and cancellous bone under oblique load (225N) was displayed in the Table 4.3 and Figure 4.2.

The result of von Mises stress percentage difference at overall the highest stress area, crown, cement between crown and CAD/CAM custom abutment, CAD/CAM custom abutment, abutment screw, cement between CAD/CAM custom abutment and Ti-base abutment, Ti-base abutment, fixture, cortical bone and cancellous bone under oblique load (225N) compared to control group (Group ZR-ZR) was displayed in the Table 4.4.

Table 4.3: Result of Load Case 2: Comparison of Von Mises Stress Of Overall The Highest Stress Area, Crown, Cement between Crown and CAD/CAM Custom Abutment, CAD/CAM Custom Abutment, Abutment Screw, Cement between CAD/CAM Custom Abutment and Ti-base Abutment, Ti-base Abutment, Fixture, Cortical Bone and Cancellous Bone Among All 5 Groups of FEA Models under Load Case 2

Group	Von Mises Stress (MPa)				
	ZR-ZR	**VSC-ZR**	**ZR-VSC**	**VST-ZR**	**ZR-VST**
Overall The Highest Stress Area	580.34	580.01	492.66	580.02	488.53
Crown	109.02	101.6	112.71	101.58	112.72
Cement between Crown & CAD/CAM Custom Abutment	15.9	71.39	29.2	76.03	29.63
CAD/CAM Custom Abutment	422.52	423.37	45.34	423.47	41.95
Abutment Screw	225.17	225.09	222.65	225.09	222.53
Cement between CAD/CAM Custom Abutment & Ti-base Abutment	19.52	19.81	54.72	19.83	57.76
Ti-base Abutment	580.34	580.01	492.66	580.02	488.53
Fixture	431.36	461.32	404.31	461.32	401.05
Cortical Bone	196.95	196.99	203.45	196.99	203.78
Cancellous Bone	4.74	4.74	4.72	4.74	4.72

ZR-ZR: CAD/CAM zirconia crown- CAD/CAM zirconia custom abutment;
VSC-ZR: 3D Printed VarseoSmile® Crown Plus crown-CAD/CAM zirconia custom abutment;
ZR-VSC: CAD/CAM zirconia crown- 3D Printed VarseoSmile® Crown Plus custom abutment;
VST-ZR: 3D Printed VarseoSmile® TriniQ® crown-CAD/CAM zirconia custom abutment;
ZR-VST: CAD/CAM zirconia crown- 3D Printed VarseoSmile® TriniQ®custom abutment

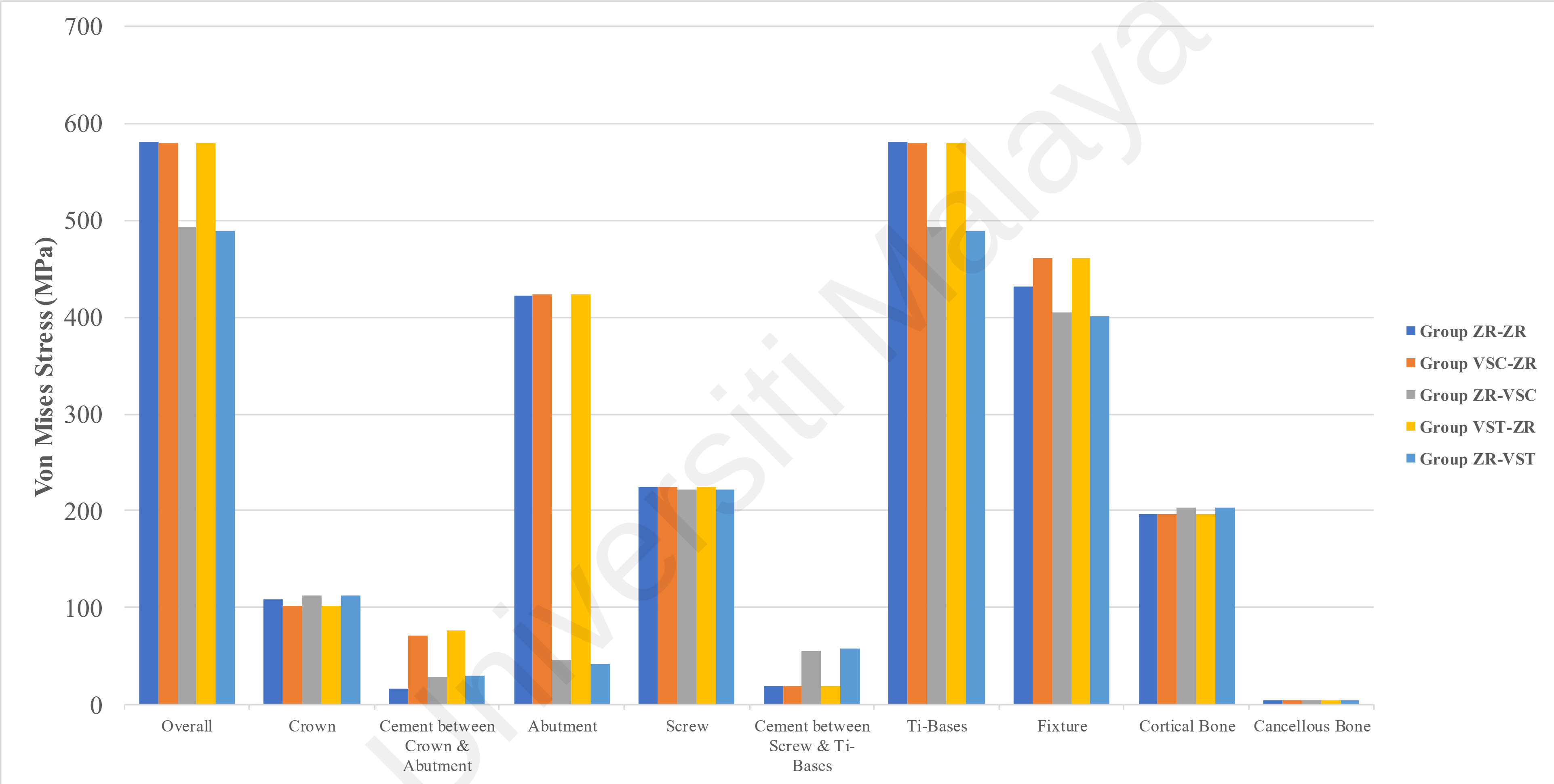


Figure 4.2: Result of Load Case 2: Comparison of Von Mises Stress Of Overall The Highest Stress Area ,Crown, Cement between Crown and CAD/CAM Custom Abutment, CAD/CAM Custom Abutment, Abutment Screw, Cement between CAD/CAM Custom Abutment and Ti-base Abutment, Ti-base Abutment, Fixture, Cortical Bone and Cancellous Bone Among All 5 Groups of FEA Models in Load Case 2

Table 4.4: Comparison of the Von Mises Stress Percentage Difference Of the Overall The Highest Stress Area, Crown, Cement between Crown and CAD/CAM Custom Abutment, CAD/CAM Custom Abutment, Abutment Screw, Cement between CAD/CAM Custom Abutment and Ti-base Abutment, Ti-base Abutment, Fixture, Cortical Bone and Cancellous Bone Among All 5 Groups of FEA Models under Load Case 2 Compared to Control Group ZR-ZR

Group	Von Mises Stress Percentage Difference (%)				
	ZR-ZR	**VSC-ZR**	**ZR-VSC**	**VST-ZR**	**ZR-VST**
Overall The Highest Stress Area	Control	-0.06	-17.80	-0.06	-18.79
Crown	Control	-7.30	3.27	-7.32	3.28
Cement between Crown & CAD/CAM Custom Abutment	Control	77.73	45.55	79.09	46.34
CAD/CAM Custom Abutment	Control	0.20	-831.89	0.22	-907.20
Abutment Screw	Control	-0.04	-1.13	-0.04	-1.19
Cement between CAD/CAM Custom Abutment & Ti-base Abutment	Control	1.46	64.33	1.56	66.20
Ti-base Abutment	Control	-0.06	-17.80	-0.06	-18.79
Fixture	Control	6.49	-6.69	6.49	-7.56
Cortical Bone	Control	0.02	3.19	0.02	3.35
Cancellous Bone	Control	0.00	-0.42	0.00	-0.42

ZR-ZR: CAD/CAM zirconia crown-CAD/CAM zirconia custom abutment;
VSC-ZR: 3D Printed VarseoSmile® Crown Plus crown-CAD/CAM zirconia custom abutment;
ZR-VSC: CAD/CAM zirconia crown-3D Printed VarseoSmile® Crown Plus custom abutment;
VST-ZR: 3D Printed VarseoSmile® TriniQ® crown-CAD/CAM zirconia custom abutment;
ZR-VST: CAD/CAM zirconia crown-3D Printed VarseoSmile® TriniQ® custom abutment

4.2.1 Overall The Highest Stress Area

Similarly, the Ti-base abutment was the most stressed location in all five groups, with values ranging from 500MPa to 600MPa. Group ZR-ZR showed the greatest stress among all five groups, at 580.34MPa. The least stress was observed at Group ZR-VST which was 488.53MPa. Groups ZR-VSC and ZR-VST showed approximately 20% less stress than the control group ZR-ZR.

4.2.2 Crown

All five groups showed comparable von Mises stress at the crown, ranging from 101.58MPa to 112.72MPa. The percentage difference in von Mises stress compared to the control group ZR-ZR was minimal. However, the stress slightly increased in the range of 3.27% to 3.28% in Groups ZR-VSC and ZR-VST, and vice versa in Groups VSC-ZR and VST-ZR which showed a decrease over 7.3%.

4.2.3 Cement between Crown and CAD/CAM Custom Abutment

The highest von Mises stress was observed in Group VST-ZR (76.03MPa), but the least in Group ZR-ZR (15.9MPa). All groups showed a 50–80% increase in von Mises stress compared to Group ZR–ZR.

4.2.4 CAD/CAM Custom Abutment

Groups ZR-VSC and ZR-VST showed significantly lower von Mises stress levels in the CAD/CAM custom abutment compared to other groups, which were 45.34MPa and 41.95MPa, respectively. There was a decline in stress of 831.89% in Group ZR-VSC and 907.2% in Group ZR-VST compared to Group ZR-ZR as a control group.

4.2.5 Abutment Screw

In general, all five groups displayed a similar pattern of von Mises stress at the abutment screw, with an average of 225MPa. Compared to the control group ZR-ZR, there was a minimal decrease in stress percentage difference from 0.04% to 1.19%.

4.2.6 Cement between CAD/CAM Custom Abutment and Ti-base Abutment

Groups ZR-VSC (54.72MPa) and ZR-VST (57.76 MPa) showed the highest von Mises stress value at the cement interface between CAD/CAM custom abutment and Ti-base abutment. There was a huge increase in stress from 64.33% to 66.20% in Groups ZR-VSC and ZR-VST compared to the control group ZR-ZR.

4.2.7 Ti-base Abutment

The Ti-base abutment had the highest stress concentration area of all the implant and bone components. Groups ZR-VSC and ZR-VST showed lower stress at 492.66MPa and 488.53MPa, respectively which was lower by almost 100MPa around 20% compared to other three groups. Groups ZR-VSC and ZR-VST showed more decrease in stress in the range of 17.80% to 18.79% at the Ti-base abutment.

4.2.8 Fixture

Comparatively, the fixture of Group ZR-VST showed the lowest von Mises stress of 401.05MPa. Group ZR-VSC demonstrated similarly low stress of 404.31MPa. Both groups exhibited a decrease of six to eight percents compared to the control group ZR-ZR unlike Groups VSC-ZR and VST-ZR showed a similarly increase 6.49% in stress.

4.2.9 Cortical Bone and Cancellous Bone

The overall stress concentration in the cortical bone which was in the range of 196.95MPa to 203.78MPa was higher than that in the cancellous bone which was in the range of 4.72MPa to 4.74MPa. It showed a minimal increase in stress in the range of

0.02% to 3.35% in cortical bone among all groups. However, there was nearly no percentage difference between all five groups in cancellous bone except groups ZR-VSC and ZR-VST, which showed a minimal decrease in stress of 0.42% compared to the control group ZR-ZR.

4.2.10 Comparison of Stress Distribution at Different Level of Components of Implant and Bone Structure under 2 Load Cases.

4.2.10.1 Overall The Highest Stress Concentration For the Whole Structure

Red label indicates the highest stress concentration area.

Table 4.5: Overall the Highest Stress Concentration for the Whole Structure under Load Case 1

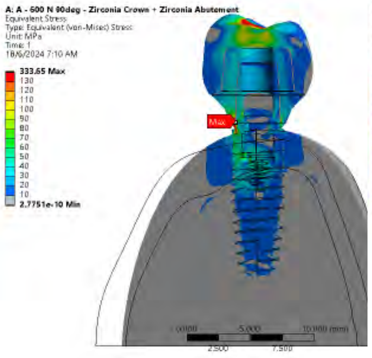
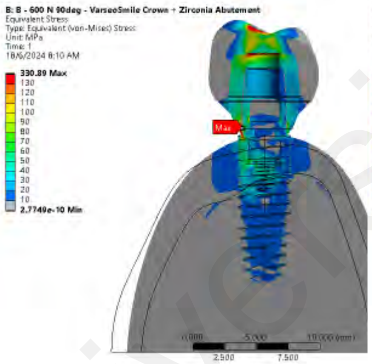
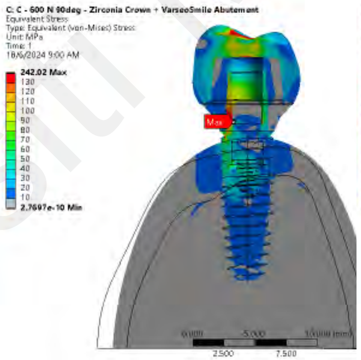
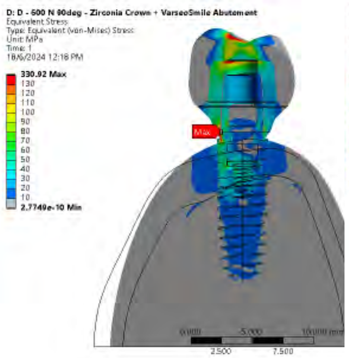
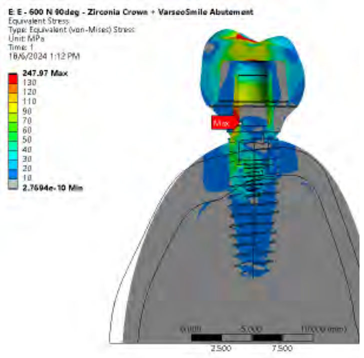
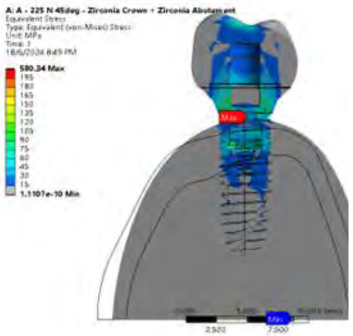
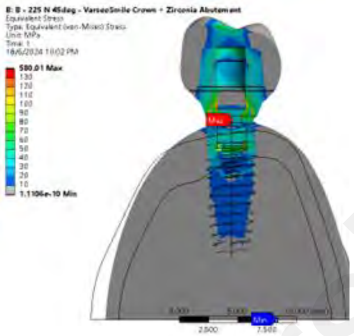
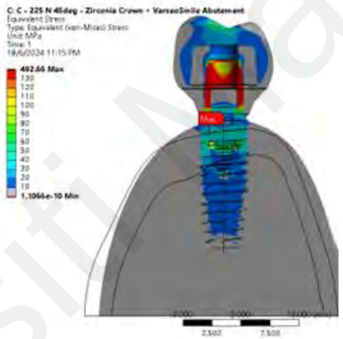
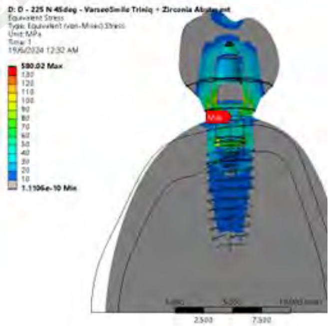
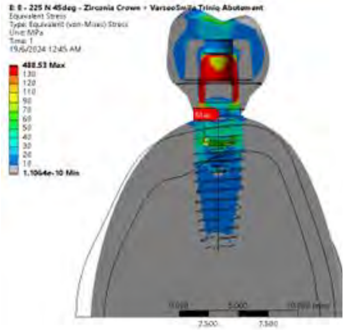
Group	ZR-ZR	VSC-ZR	ZR-VSC	VST-ZR	ZR-VST
Load Case 1					
Von Mises Stress (MPa)	**333.65**	**330.89**	**242.02**	**330.92**	247.97

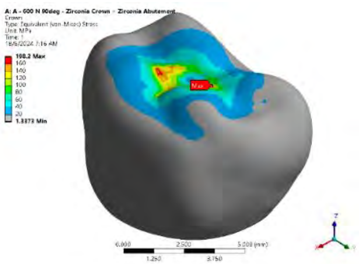
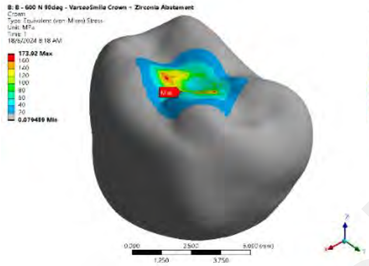
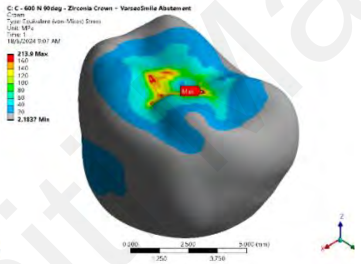
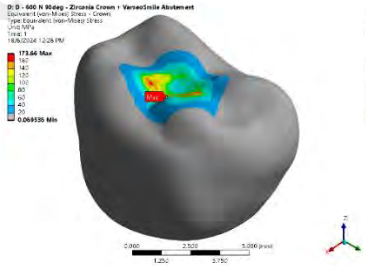
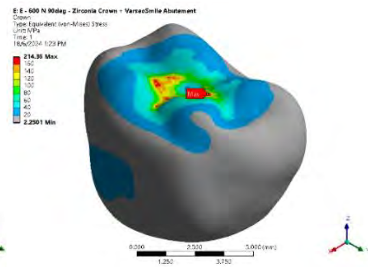
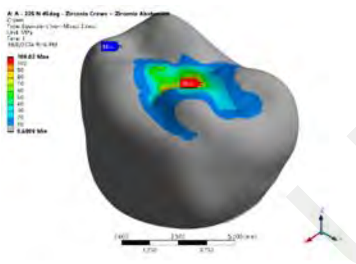
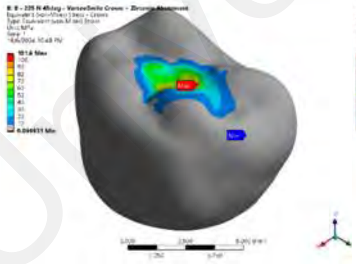
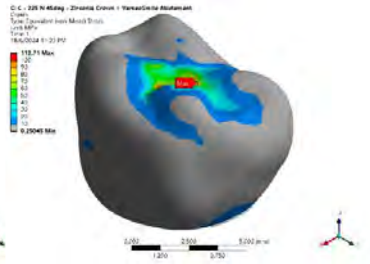
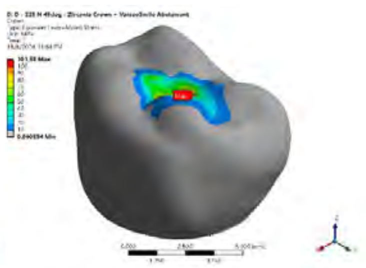
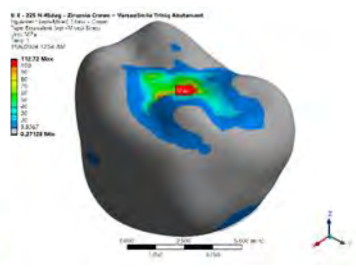
Table 4.6: Overall the Highest Stress Concentration for the Whole Structure under Load Case 2

Group	ZR-ZR	VSC-ZR	ZR-VSC	VST-ZR	ZR-VST
Load Case 2					
Von Mises Stress (MPa)	580.34	580.01	492.66	580.02	488.53

In Load Case 1, the neck region of implant-abutment connection contained the majority of stress concentration. Most stress was concentrated at the middle region of implant-abutment connection in Load Case 2. Overall, Group ZR-VSC and Group ZR-VST showed the least von Mises stress value which were 242.02MPa and 247.974MPa under vertical load respectively; 492.66MPa and 488.53MPa under oblique load correspondingly, especially at the abutment level.

4.2.10.2 Crown

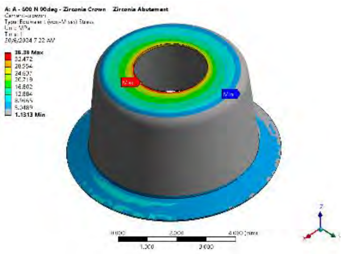
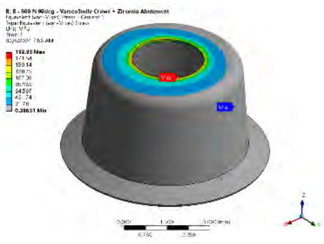
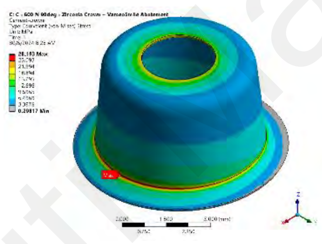
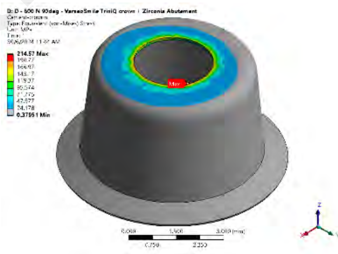
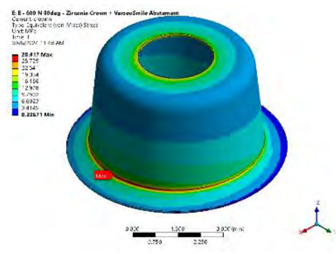
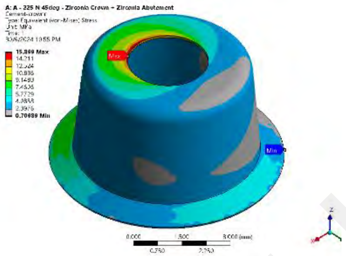
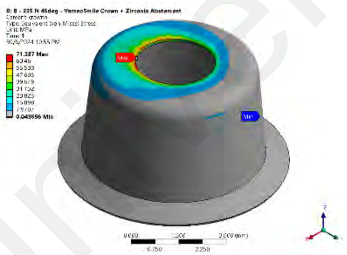
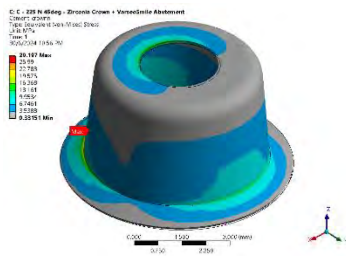
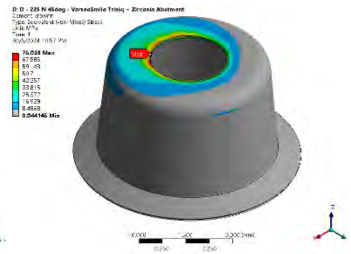
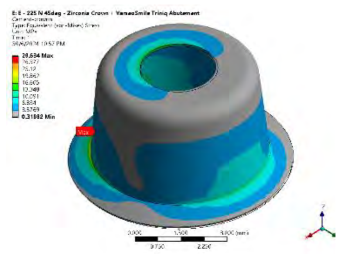
Table 4.7: Stress Distribution at the Crown under the Two Load Cases

Group	ZR-ZR	VSC-ZR	ZR-VSC	VST-ZR	ZR-VST
Load Case 1					
Von Mises Stress (MPa)	198.20	173.92	213.9	173.66	214.39
Load Case 2					
Von Mises Stress (MPa)	109.02	101.6	112.71	101.58	112.72

The majority of stress concentration was located at the occlusal areas of crown in Load Case 1 and 2.

4.2.10.3 Cement Between the Crown & CAD/CAM Custom Abutment under 2 Load Cases

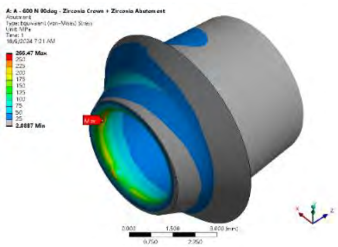
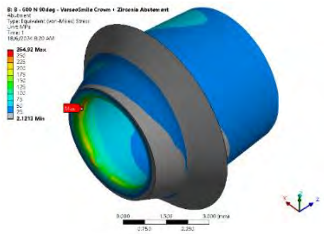
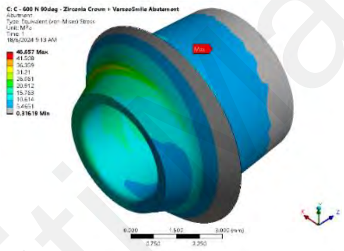
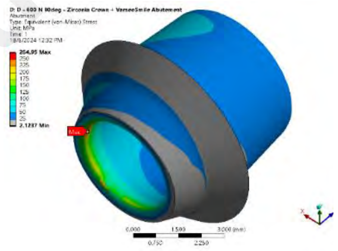
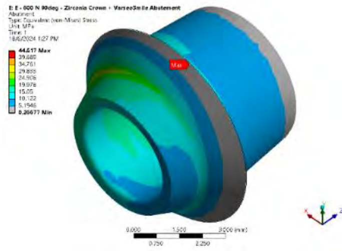
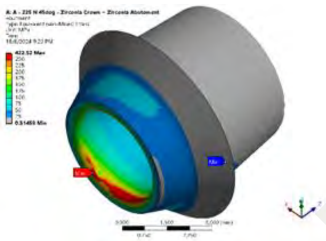
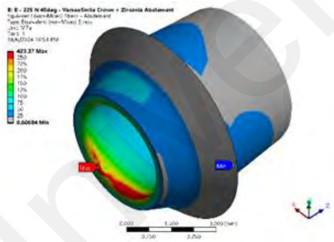
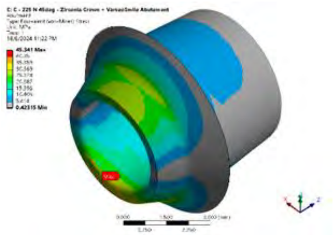
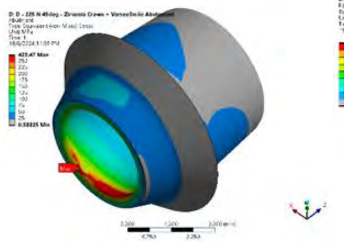
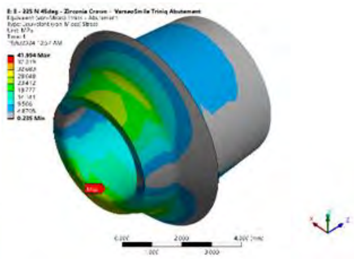
Table 4.8: Stress Distribution between Cement Between the Crown & CAD/CAM Custom Abutment under 2 Load Cases

Group	ZR-ZR	VSC-ZR	ZR-VSC	VST-ZR	ZR-VST
Load Case 1					
Von Mises Stress (MPa)	36.39	192.93	28.19	214.57	28.92
Load Case 2					
Von Mises Stress (MPa)	15.90	71.39	29.20	76.03	29.63

Under Load Case 1 and 2, Group ZR-VSC and ZR-VST demonstrated the stress concentration at the cement layer of neck region of CAD/CAM custom abutment whereby Group ZR-ZR, VSC-ZR and Group VST-ZR at the cement layer of top region of CAD/CAM custom abutment.

4.2.10.4 CAD/CAM Custom Abutment

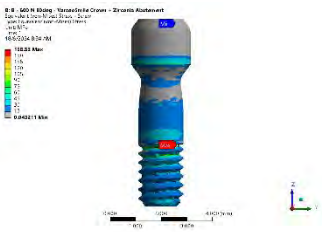
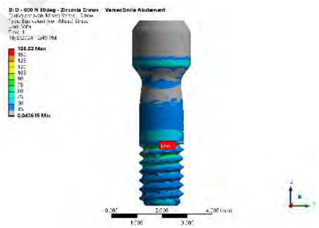
Table 4.9: Stress Distribution at the CAD/CAM Custom Abutment under the Two Load Cases

Group	ZR-ZR	VSC-ZR	ZR-VSC	VST-ZR	ZR-VST
Load Case 1					
Von Mises Stress (MPa)	266.47	264.92	46.66	265.63	44.62
Load Case 2					
Von Mises Stress (MPa)	422.52	423.37	45.34	423.47	41.95

In Load Case 1, all groups showed the stress concentration area of the CAD/CAM custom abutment at the internal connection between CAD/CAM custom abutment and Ti-base abutment except Group ZR-VSC at the body of abutment; Group ZR-VST at the collar area at gingival level. In Load Case 2, all five groups showed the stress concentration area at the internal connection CAD/CAM custom abutment and Ti-base abutment.

4.2.10.5 Abutment Screw

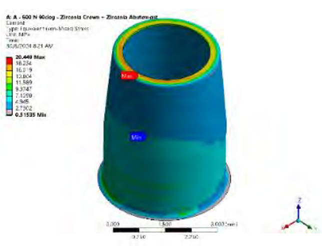
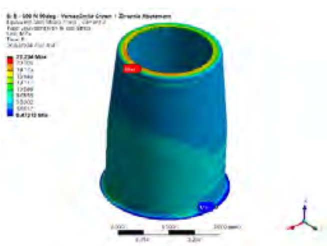
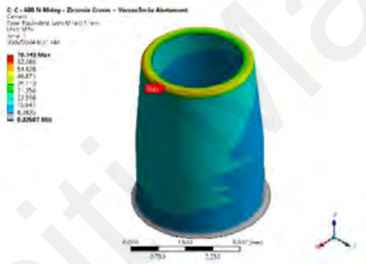
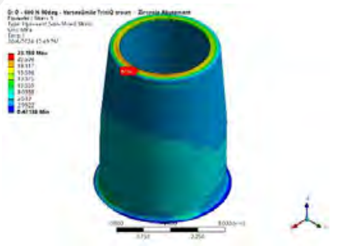
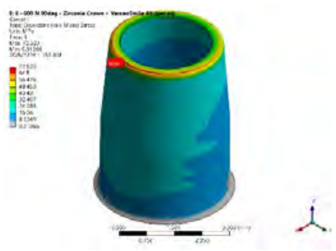
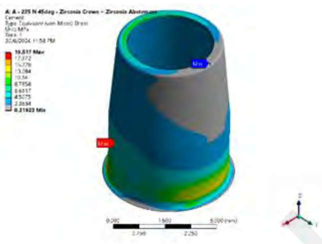
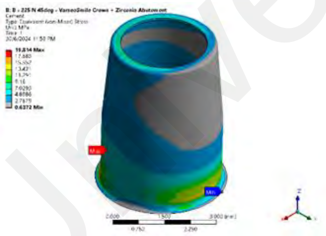
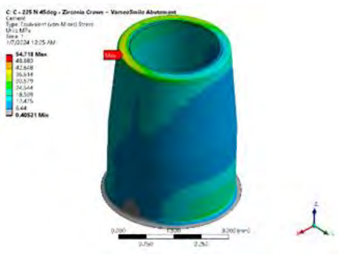
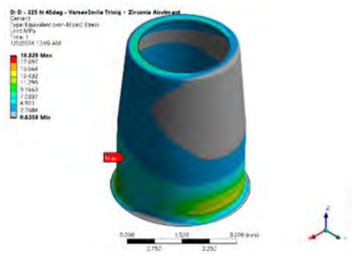
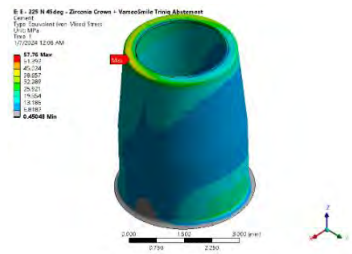
Table 4.10: Stress Distribution at the Abutment Screw under 2 Load Cases

Group	ZR-ZR	VSC-ZR	ZR-VSC	VST-ZR	ZR-VST
Load Case 1					
Von Mises Stress (MPa)	158.68	158.53	157.84	158.52	157.82
Load Case 2					
Von Mises Stress (MPa)	225.17	225.09	222.65	225.09	222.53

The stress concentration at the abutment screw among five groups in Load Case 1 and 2 was situated at the first thread of abutment screw.

4.2.10.6 Cement between the CAD/CAM Custom Abutment and Ti-base Abutment

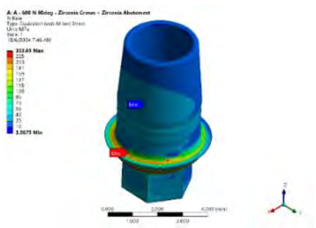
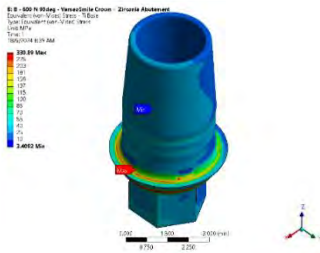
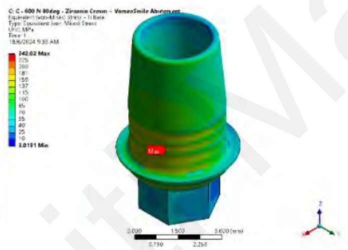
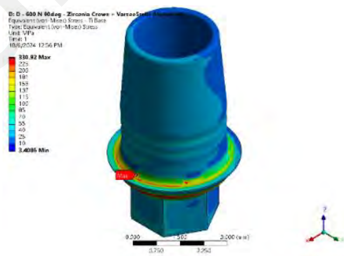
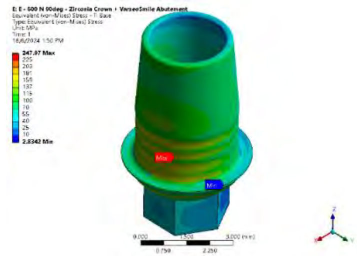
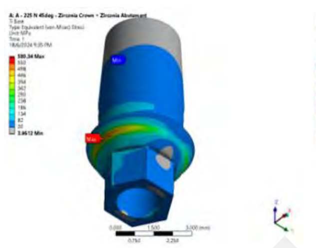
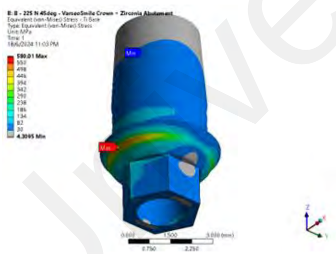
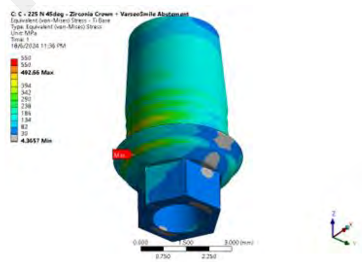
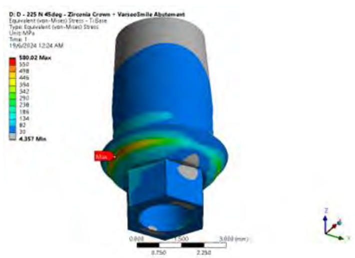
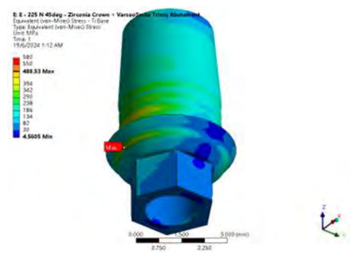
Table 4.11: Stress Distribution of Cement between the CAD/CAM Custom Abutment and Ti-base Abutment under 2 Load Cases

Group	ZR-ZR	VSC-ZR	ZR-VSC	VST-ZR	ZR-VST
Load Case 1					
Von Mises Stress (MPa)	20.45	23.23	70.14	23.16	72.52
Load Case 2					
Von Mises Stress (MPa)	19.52	19.81	54.72	19.83	57.76

The stress concentration area of all groups under Load Case 1 was the cement layer of the of top region of T-base abutment. Under Load Case 2, Group ZR-ZR, VSC-ZR, VST-ZR showed stress concentration area at the cement layer of neck region of Ti-base abutment. Group ZR-VSC and VST-ZR showed the stress concentration area at the top region of Ti-base abutment.

4.2.10.7 Ti-base Abutment

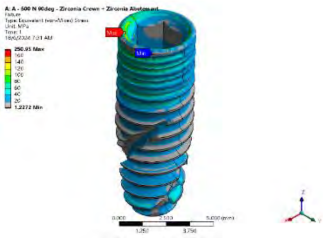
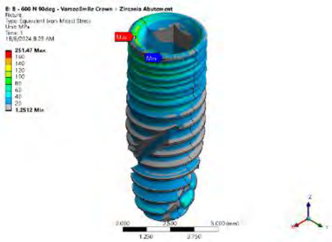
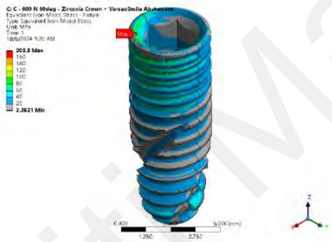
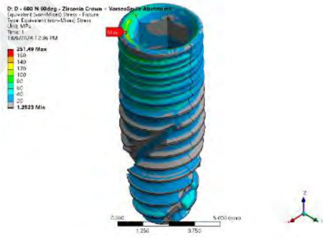
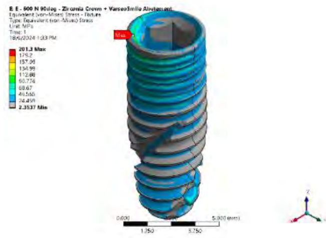
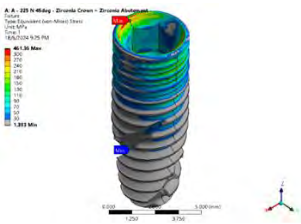
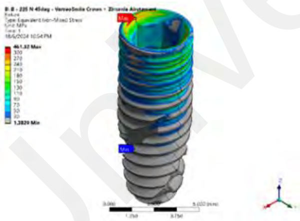
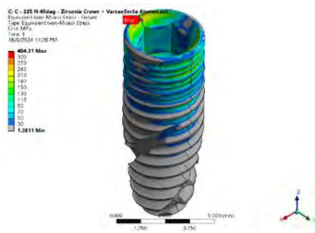
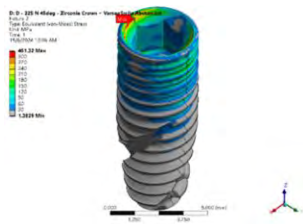
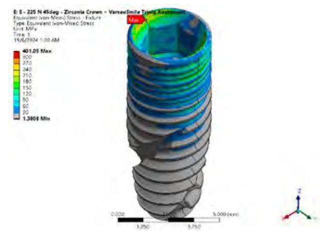
Table 4.12: Stress Distribution of Ti-base Abutment under 2 Load Cases

Group	ZR-ZR	VSC-ZR	ZR-VSC	VST-ZR	ZR-VST
Load Case 1					
Von Mises Stress (MPa)	**333.65**	**330.89**	**242.02**	**330.92**	**247.97**
Load Case 2					
Von Mises Stress (MPa)	**580.34**	**580.01**	**492.66**	**580.02**	**488.53**

In Load Case 1, Groups ZR-ZR, VSC-ZR and VST-ZR showed the stress concentration area at the cervical area of Ti-base abutment, whereas Group ZR-VSC and ZR-VST showed the stress concentration area at the body above the cervical area of Ti-base abutment. In Load Case 2, all groups showed the stress concentration area at the cervical area of Ti-base abutment.

4.2.10.8 Fixture

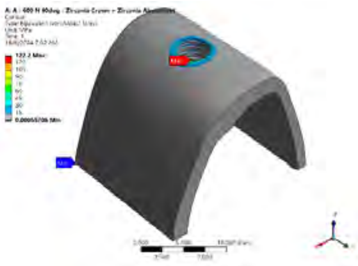
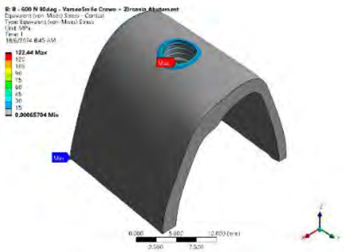
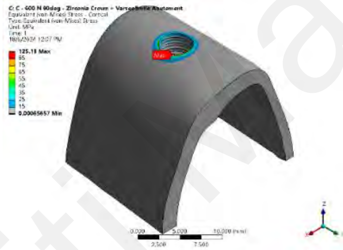
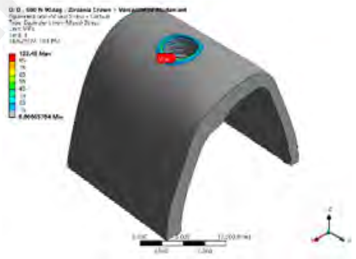
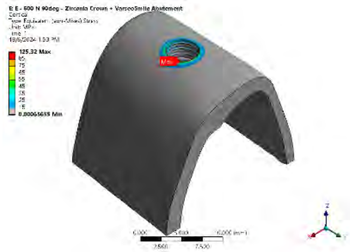
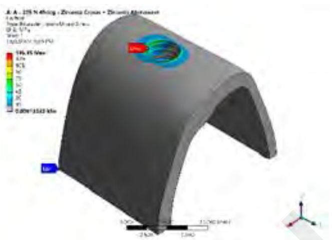
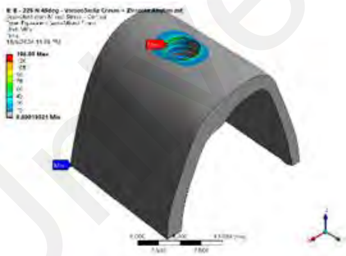
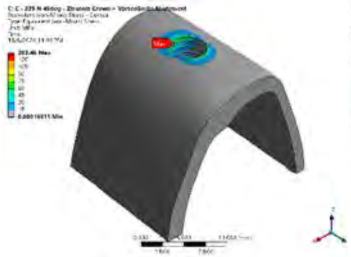
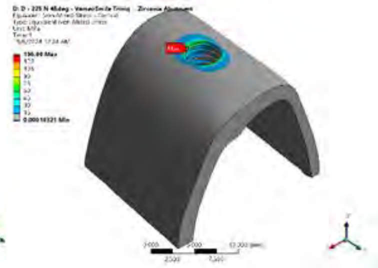
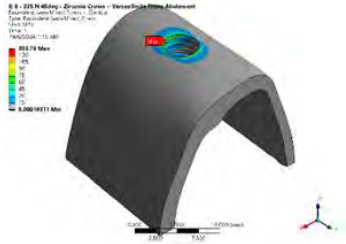
Table 4.13: Stress Distribution of Fixture in 2 Load Cases

Group	**ZR-ZR**	**VSC-ZR**	**ZR-VSC**	**VST-ZR**	**ZR-VST**
Load Case 1					
Von Mises Stress (MPa)	**250.95**	**251.47**	**203.8**	**251.49**	**201.3**
Load Case 2					
Von Mises Stress (MPa)	**431.36**	**461.32**	**404.31**	**461.32**	**401.05**

In Load Case 1 and 2, all groups showed the stress concentration area at the neck of fixture (platform).

4.2.10.9 Cortical Bone

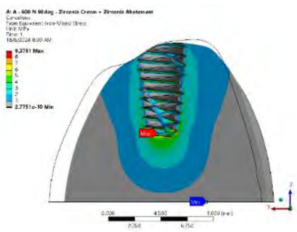
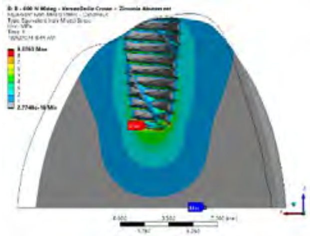
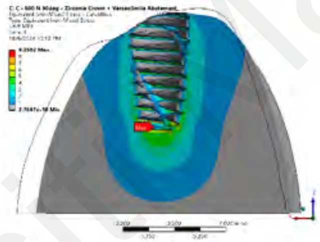
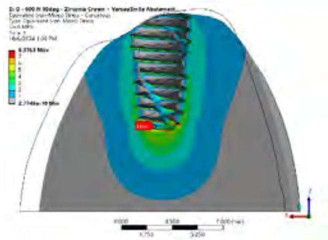
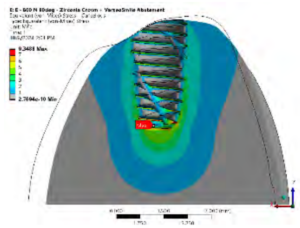
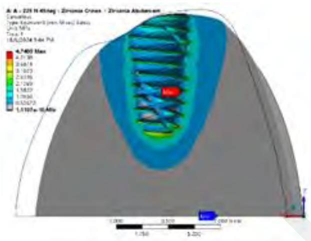
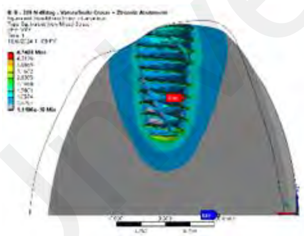
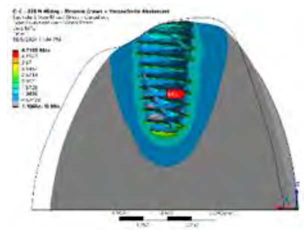
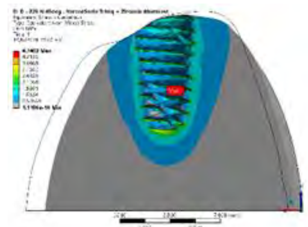
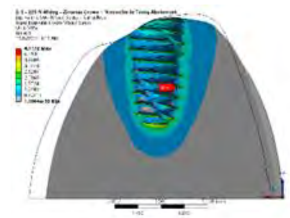
Table 4.14: Stress Distribution of Cortical Bone in 2 Load Cases

Group	ZR-ZR	VSC-ZR	ZR-VSC	VST-ZR	ZR-VST
Load Case 1					
Von Mises Stress (MPa)	122.2	122.44	125.19	122.45	125.32
Load Case 2					
Von Mises Stress (MPa)	196.95	196.99	203.45	196.99	203.78

In Load Case 1 and 2, all groups showed the stress concentration area at the bone-implant connection at the neck region.

4.2.10.10 Cancellous Bone

Table 4.15: Stress Distribution of Cancellous Bone in 2 Load Cases

Group	ZR-ZR	VSC-ZR	ZR-VSC	VST-ZR	ZR-VST
Load Case 1					
Von Mises Stress (MPa)	9.38	9.38	9.35	9.38	9.35
Load Case 2					
Von Mises Stress (MPa)	4.74	4.74	4.72	4.74	4.72

For the cancellous bone, the stress concentration area was at the connection between fixture and cancellous bone, generally comparable among all five groups in Load Cases 1 & 2.

CHAPTER 5: DISCUSSION

5.1 Methodology

This study was aimed to evaluate the stress distribution in different components of implant and peri-implant bone by comparing 3D printed ceramic filled hybrid materials and CAD/CAM zirconia as CAD/CAM custom abutment for permanent implant-supported crown using a finite element study model.

FEA was chosen for this study because it effectively simulates and predicts the physical behaviour of structures and materials under mechanical forces, including biological systems. As a numerical method, FEA analyses stress and deformations in structures. It is widely used in implantology to assess stress patterns in implant components and peri-implant bone structures, as evidenced by numerous previous studies. Comparatively, it is non-invasive, more cost- and time-saving than in vivo and in vitro studies by altering multiple test parameters in complex body geometries and it can provide more data and predict the problem before the in vitro studies (Baggi et al., 2008; Baggi et al., 2013; Baggi et al., 2014; Hasan et al., 2012; Jemaa et al., 2023b; Lisiak-Myszke et al., 2020; Moris et al., 2017).

Static loading was chosen as the load application in this study as it is the most commonly used in the previous FEA. Static loading remains a crucial component of materials testing. It offers a controlled and simplified environment to understand more fundamental material properties, and this understanding is vital when interpreting the more complex results obtained under dynamic loading conditions. Besides, static loading was applied from the maxilla to the mandible, assuming no mandibular movement and maintaining a constant intensity over time (Cantó-Navés et al., 2021; Geng et al., 2001; I et al., 2016). This study was aimed to analyse the stress distribution in each component of implant and surrounding bone structure. A static and constant loading could predict pattern of stress distribution in each level. In this study load case 1, vertical load was applied along the long axis of implant onto the occlusal surface of implant-supported crown representing mandibular first molar (Alemayehu & Jeng, 2021; Amaral et al., 2018; Huang & Wang, 2019).

A vertical load of 600 N was applied in this study, in accordance with previous researches. This load simulated the occlusal forces exerted by a food bolus on the central fossa of an implant crown and was applied axially along the implant axis (Ausiello et al., 2019; Ausiello et al., 2022; Ausiello et al., 2023; Dal Piva et al., 2018; Gomes de Carvalho et al., 2021; Lin et al., 2020; Tribst et al., 2024). The 600 N force represented the maximum bite force recorded for a mandibular first molar and was consistent with the typical range of biting forces, which can vary from 20 to 1000 N in osseointegrated implants (Duan & Griggs, 2015; Elsyad & Khairallah, 2017; Hojjatie & Anusavice, 1990; Müller et al., 2012).

For load case 2, an oblique load of 225 N was applied at an angle of 45° to the implant crown axis. This oblique load represented approximately 37-40% of the maximum masticatory load. This orientation was chosen to simulate lateral forces encountered during mastication in a clinical setting (Gibbs et al., 1981; Liu et al., 2011; Lundgren & Laurell, 1986; Yoon et al., 2018).

3D printed ceramic filled hybrid materials including VarseoSmile® Crown Plus and VarseoSmile ®TriniQ® were chosen as implant supported crown and abutment material in this study. Compared to zirconia, resin-based restorative materials may help to reduce the stress on both the implant component and the peri-implant bone according to the previous studies (Skalak, 1983). VarseoSmile® Crown Plus, introduced in February 2020, is a novel material designed for additive manufacturing of permanent tooth-colored restorations. It is approved for single-tooth restorations such as full crowns, inlays, onlays, and veneers, and is the first 3D-printable material approved for definitive dental restorations. This material is a ceramic-infiltrated hybrid composite, consisting of a methacrylic ester matrix with ceramic fillers, and is classified as a "resin matrix ceramic". Similarly, VarseoSmile®TriniQ® is addition to the innovative 3D printing materials following establishment of VarseoSmile® Crown Plus. It has demonstrated enhanced material stability and maximum flexibility, making it suitable for both permanent bridge restorations and extensive temporaries and has meet the diverse requirements of modern dental treatments. Given its properties, there is considerable interest in studying how VarseoSmile®TriniQ® and other novel 3D-printed resin-based materials influence stress distribution in permanent implant-supported restorations. Hence, further research is required to study and analyse the mechanical properties of these new materials before they are commonly practised (Graf et al., 2022).

A mandibular first molar implant-supported crown was designed with the minimum wall thicknesses of 1 mm following the instructions by manufacturer,. The crown was designed was 8.5mm buccolingual width, 6.5mm occlusocervical height and 9.5mm mesiodistal length. The thickness of resin cement layer was set at 50 μm, following International Organization for Standardization (ISO) 4049:2019 (Bagheri, 2013; Mehl et al., 2013; Suksuphan et al., 2024).

5.2 Stress Distribution

5.2.1 Crown

Among the five groups regardless the load application, zirconia crown showed higher von Mises stress value than VarseoSmile® Crown Plus and VarseoSmile ®TriniQ® crown in which zirconia crown showed stress higher than 190MPa compared to VarseoSmile® Crown Plus and VarseoSmile ®TriniQ® crowns which showed 173.92MPa and 173.66MPa respectively, under Load Case 1. The similar pattern of stress value was noted in Load

Case 2 in which zirconia crown showed stress higher than 109MPa compared to VarseoSmile® Crown ^{Plus} and VarseoSmile ®TriniQ® crown which showed 101.6MPa and 101.58MPa respectively. The possible reason of lower stress value of the novel 3D printed ceramic filled hybrid materials showed in this study could be its ability to withstand impact force via dampening effect and dissipate elastic energy to surrounding structures by allowing viscoelastic deformation. On the other hand, zirconia, with its higher modulus of elasticity, tends to allocate elastic energy without significant damping effects, thus transferring the elastic energy to the immediate vicinity. Further research is needed to support this observation. The crystallinity of crown materials also plays a significant role in stress distribution, with higher crystallinity leading to increased stress concentration within the material (Soares et al., 2021). This finding aligned with the results observed by Sevimay and Usumez, who compared various combinations of zirconia and 3D printed ceramic filled hybrid materials. Their investigation revealed that different restorative materials for crowns and abutments notably affected both the magnitude and distribution of stresses in the superstructure and the implant (Sevimay, Usumez, et al., 2005). This variation was likely attributable to differences in the modulus of elasticity between zirconia and 3D printed ceramic filled hybrid materials. Specifically, a higher modulus of elasticity tends to concentrate greater stress within the material. These results corroborated the results of studies that evaluated implant-supported crowns of different materials and which verified that crown with a high modulus of elasticity hinders masticatory load dissipation. This study result also aligned with Tribst's study compared zirconia, lithium disilicate and hybrid ceramic in nine different combinations, a crown with higher modulus of elasticity combined with hybrid abutment with lower modulus of elasticity reduced the tensile stress concentration in the restoration cervical region (J. Tribst et al., 2019).

5.2.2 Cement

Cement layer between crown and CAD/CAM custom abutment in Group ZR-VSC and ZR-VST showed less von Mises stress which were 28.19MPa and 28.92MPa respectively, under Load Case 1; 29.2MPa and 29.63MPa respectively in Load Case 2. The abutment was made up of 3D printed ceramic filled hybrid materials which has lower modulus of elasticity and its ability to dissipate the energy to the surrounding structure. Sannino et al. found that the stress gradient between a crown and a customized abutment, as well as between an abutment and a titanium base abutment, increased when the materials had different moduli of elasticity. This effect was less pronounced when both materials had similar moduli (Sannino et al., 2010). Stress distribution became non-homogeneous when materials with different elastic moduli were combined. In rigid systems where both the crown and the titanium abutment had a high modulus of elasticity as in Groups ZR-ZR, VSC-ZR, and VST-ZR, the cementing line was less likely to deform, leading to reduced stress generation in this area (J. P. M. Tribst et al., 2019). Conversely, when the abutment had a low modulus of elasticity and the titanium base abutment had a high modulus of elasticity as in Groups ZR-VSC and ZR-VST, the stress concentration in the resin cement layer increased which is less than compressive strength of cement that is more than 200MPa

5.2.3 CAD/CAM Custom Abutment and Abutment Screw

For the CAD/CAM custom abutment, Groups ZR-VSC and ZR-VST showed the least von Mises stress value which were 46.66 MPa and 44.62 MPa respectively, in Load Case 1 and 45.34MPa and 41.95MPa respectively in Load Case 2. In our study, whenever the abutment material was 3D printed ceramic filled hybrid materials, it showed drastic decrease of von Mises stress from sixfold to tenfold. The possible reason was 3D printed ceramic filled hybrid materials had lower modulus of elasticity and more resilient. It absorbed the energy and distributed force evenly. And as it had higher flexural strength hence it could resist the deformation under load (A. Alshamrani et al., 2023; Gad & Fouda, 2023). The stress distribution pattern in abutment screw among five groups were comparable regardless the different crown and abutment materials as well as load application. This could be because stress was typically concentrated at the implant neck, abutment margin, transgingival area, as well as on the flat area and first thread of the abutment screw. The results of this study were consistent with previous findings, which showed that overall stress concentration across the implant, including the prosthetic components, fixture, and surrounding bone structure, was reduced in Groups ZR-VSC and ZR-VST. Notably, there was a significant decrease in stress at the abutment level under both vertical and oblique loads (Alvarez-Arenal et al., 2013; Cağlar et al., 2006).

Polymer CAD/CAM resin materials and composites demonstrated higher damping values compared to metals and ceramics, with composites exhibiting significantly greater damping capabilities than polymers. Materials with lower filler percentages and higher resin/polymer content showed a more pronounced viscoelastic damping effect. In this study, it was also observed that abutment materials with a lower modulus of elasticity reduced stress concentration in the Ti-base abutment (Niem et al., 2022). In this study, the findings also showed the abutment material with lower modulus of elasticity reduced stress concentration in the Ti-base abutment.

The critical stress concentration region above the first thread of abutment screw was similar to the literature. This origin of stress concentration for the abutment screw couldn't be modified by different combination of zirconia and 3D printed ceramic filled hybrid materials, possibly leading to torque loss or fracture of the abutment screw (Coppedê et al., 2009).

5.2.4 Ti-base Abutment

The Group ZR-VSC and ZR-VST showed greater decrease in concentration of von Mises stress at Ti-base abutment regardless load application in which Group ZR-VSC showed 242.02MPa and 492.66MPa under Load Case 1 and 2 respectively. Group ZR-VST showed 247.97MPa and 488.53MPa under Load Case 1 and 2 respectively. This could be explained that the stress well distributed at the abutment made up of 3D printed ceramic filled hybrid materials which dissipated the energy without causing deformation. Ti-base abutment showed the most stress concentration area among other components, it could be correlated to its high modulus of elasticity. As the connecting part between the fixture and implant superstructure, they must ensure uniform stress distribution to minimise technical complications (Al-Thobity, 2021). This observation was consistent with previous studies that emphasised stress concentration in the cervical area of the titanium base abutment, affecting the prosthetic connection (Balik et al., 2012; da Silva et al., 2014). This study demonstrated that Ti-base abutments exhibited the highest stress levels among the components, highlighting their critical role in receiving and transmitting occlusal forces to the implant, abutment screw, and peri-implant bone. This finding aligned with the results of a previous study by Canullo et al. (Canullo et al., 2020)

5.2.5 Fixture

Group ZR-VSC and ZR-VST showed decrease in von Mises stress in fixture in Load Case 1 and 2 (Group ZR-VSC: 203.8MPa; 404.31MPa) (Group ZR-VST: 201.3MPa; 401.05MPa). This was possible due to incorporation of 3D printed ceramic filled hybrid materials with lower modulus of elasticity hence reduced stress concentration in the fixture. Previous research exhibited high stress concentration observed at the first thread of the implant fixture (Udomsawat et al., 2019).

5.2.6 Cortical Bone and Cancellous Bone

The result of von Mises stress value in cortical bone in Load Case 1 (122.2MPa to 125.32 MPa) and in Load Case 2 (196.95MPa to 203.78MPa) as well as cancellous bone under Load Case 1 (9.35MPa to 9.38MPa) and under Load Case 2 (4.72MPa to 4.74MPa) indicated that the combination of different restorative and abutment materials with varying moduli of elasticity did not significantly affect stress distribution to the peri-implant bone structure as it is still less than the compressive strength of cortical bone which is 100MPa to 130MPa and it was minimal increase of 3MPa range. This was attributed to the similar biomechanical behaviour of these materials.

Our findings aligned with the study by El-Anwar et al. , which demonstrated that changes in abutment manufacturing materials did not alter stress and deformation distributions. Although variations in abutment materials had no significant effect on the cortical and spongy bone stress, it was recommended to use softer abutment materials to absorb more energy and reduce stress transferred to the crown, implant, and surrounding bone (El-Anwar, 2013).

Additionally, our results were consistent with previous research by Gökçimen et al, which also found that variations in crown materials did not impact stress concentration in the peri-implant bone (Gökçimen et al., 2024).

5.2.7 Overall

Overall, the von Mises stress observed at the CAD/CAM custom abutment (44.62MPa to 266.47MPa), fixture (201.3MPa to 251.49MPa) and cortical bone (122.2MPa to 125.32MPa) for all five groups in this study showed higher value in Load Case 1 compared to Load Case 2 in which CAD/CAM custom abutment from 41.95MPa to 423.47MPa , fixture from 401.05MPa to 461.32MPa, cortical bone from 196.95MPa to 203.78MPa. Oblique load did not only exert compressive stress, but also tensile stress and shear force on the implant and bone structure. This result was in agreement with previous studies showing the stress of the whole implant and peri-implant bone in oblique load was higher than axial load, about two to ten times (de Souza Rendohl & Brandt, 2020; Rezende et al., 2015). In addition, it was also in agreement with the study conducted by Takahashi et al. to assess the impact of different types of loading on the stress levels of implant-supported partial dentures. It was found that oblique loads resulted in increased stress on both the prosthesis and the surrounding bone structure (Takahashi et al., 2015). De Faria Almeida et al. conducted a study to assess the impact of various implant-abutment connections on bone stress when subjected to axial and oblique pressures. The previous study also agreed with this finding, indicating oblique loads considerably increased stress in all components of the implants as well as the bone structure (Chang et al., 2013; de Faria Almeida et al., 2014).

Sevimay et al. and Vieira et al. discussed the positive effect of the modulus of elasticity of a material on the stress distribution in the abutment and crown, but it has no effect on the amount or distribution of stress in the bone tissue (Sevimay, Usumez, et al., 2005; Vieira et al., 2023). It was consistent with this result.

3D printed ceramic filed hybrid material was used in our study as it was resin material with incorporation of nano ceramic particles by referring to a study conducted by Duan et al to compare the stress distribution in lithium disilicate ceramic and resin nanoceramic CAD/CAM crowns under vertical loading. It was reported that resin nanoceramic crowns showed lower stress values. (Duan & Griggs, 2015), which was accordance with the result in this study.

The findings of the previous study by Ercal et al. corroborated the findings of this study, indicating that stress was predominantly concentrated in the cortical bone surrounding the neck region of the implant, rather than in the apical region (Ercal et al., 2021) .

5.3 Limitations

The static force alone couldn't simulate real oral environment. It must be combined with the dynamic force which was related to chewing, swallowing and eccentric occlusion in masticatory system producing more critical effect. The masticatory occlusal load applied to the crown surface should be cyclic, repeatable, and dynamic with time(Liu et al., 2019).

The present study was a theoretical analysis to evaluate the biomechanical behavior of materials. However, there were inherent limitations that should be clarified by further data prior to definitive clinical recommendations. The absence of variables such as pH changes, biofilm and temperature were some of the major limitations. The finite element method could identify regions under stress and regions of possible failures according to the geometry and mechanical behavior of dental materials. However, fatigue lifetimes (S-N curves) should be determined for restorative materials, to provide a more complete in vitro evaluation. This was a pilot study and 3D printed resin need to be subjected to further research incorporating intraoral simulative parameters to validate as aviable technology for the fabrication of ceramic restorations in clinical dentistry. The assumption of the materials homogeneously linear, static and isotropic and 100% osseointegration did not simulate the real clinical scenario. There was absence of cyclic loading (Giovani et al., 2009) and thermocycling effect.

CHAPTER 6: CONCLUSION

Within the limitations of current study, combination of implant-supported crown and CAD/CAM custom abutment of different moduli of elasticity such as CAD/CAM zirconia and 3D printed ceramic filled hybrid materials have positive influence on the stress distribution at the crown, cement between crown and CAD/CAM custom abutment, CAD/CAM custom abutment, abutment screw, cement between CAD/CAM custom abutment and Ti-base abutment, Ti-base abutment and fixture.

However, the change in implant-supported crown and CAD/CAM custom abutment showed no effect on the stress distribution in peri-implant bone structure.

3D printed ceramic filled hybrid materials offer significant advantages in reducing stress concentration mainly in CAD/CAM custom abutment followed by Ti-base abutment and fixture. Hence, it could be a viable alternative material for abutment material in order to reduce stress concentration at other components of implant to minimise mechanical complications.

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