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Effect of Crown-Implant Ratio on Stress Distribution around Implant Restored With Different Crown Materials: A Finite Element Analysis

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ABSTRACT
The biomechanical success of implant-supported restorations depends significantly on the crown-to-implant (C/I) ratio and restorative material. This study aimed to evaluate the effect of different C/I ratios (1:1, 1.5:1, and 2:1) on stress distribution around dental implants restored with zirconia and polyetheretherketone (PEEK) crowns, using three-dimensional finite element analysis (FEA). A mandibular first premolar region was modeled, and six 3D finite element models were generated with Osstem implants (4 mm × 10 mm) restored with either zirconia or PEEK crowns. Vertical (200 N) and oblique (100 N) loads were applied, and von Mises stress distribution was analyzed in peri-implant bone, implant, abutment, abutment screw, and crown.
Results revealed that increasing the C/I ratio led to higher stress concentration, particularly under oblique loading. Stress values were predominantly localized in the crestal bone and implant neck region. Zirconia crowns exhibited higher internal stresses due to their higher elastic modulus, but no substantial difference was observed in stress transfer to the implant or surrounding bone when compared with PEEK crowns. Clinically, maintaining a low C/I ratio and minimizing oblique loading are crucial to reducing biomechanical risks. Within the study limitations, crown material had minimal influence compared to the C/I ratio on peri-implant stress distribution.

Keywords: Crown-to-implant ratio, finite element analysis, zirconia, PEEK, stress distribution, implant biomechanics.

I. INTRODUCTION

Dental implants are widely regarded as the preferred solution for replacing missing teeth, offering both aesthetic and functional benefits. Their long-term success, however, depends on several biomechanical considerations, with stress distribution around the implant and surrounding bone being particularly crucial. Improper stress concentration can result in complications such as bone loss and implant failure. Factors such as implant design, dimensions, bone quality, and prosthetic components—including the crown-to-implant ratio—play an essential role in managing these stresses effectively.

The crown-to-implant ratio (CIR) describes the proportional relationship between the crown height and the length of the implant. This ratio is influenced by the location of the implant, bone resorption patterns, and duration of tooth loss. An increased CIR, particularly in cases involving shorter or narrower implants, may amplify stress at the bone-implant interface, potentially compromising the stability of the restoration.

Numerous studies have explored how variations in CIR impact stress distribution. Elevated CIRs are typically associated with greater stress loads, especially in areas with low bone density. Research has shown that higher CIRs lead to increased mechanical stress, which may affect implant performance and longevity, particularly under dynamic loading conditions.

The material used for the prosthetic crown also significantly affects stress transmission. Common materials such as zirconia and polyetheretherketone (PEEK) differ in their mechanical behavior. Zirconia, a high-strength ceramic, offers durability and esthetics but can concentrate stress due to its stiffness. Conversely, PEEK is a flexible polymer with good biocompatibility and a lower elastic modulus, which can help to dampen stress and distribute it more evenly around the bone.

Finite element analysis (FEA) has been widely used to assess the biomechanical implications of CIR in conjunction with different restorative materials. Studies indicate that higher CIRs in short implants increase stress concentrations, while the choice of crown material can further influence these effects. For instance, zirconia tends to intensify stress at the implant interface, while PEEK may offer a stress-reducing effect.

Although existing literature has addressed CIR’s impact on implant biomechanics, comparative data on zirconia and PEEK crowns under varying CIR conditions remain limited. Understanding how these materials behave under different biomechanical scenarios is important for enhancing clinical outcomes.

This study aims to evaluate the influence of different crown-to-implant ratios on stress distribution using FEA, specifically comparing zirconia and PEEK crowns. By examining how these materials perform under varying conditions, the research seeks to provide clinicians with insights that can improve implant restoration planning and contribute to more predictable long-term results

II. MATERIAL AND METHODS

This in vitro study aimed to analyze different crown-to-implant ratios (CIRs) and crown materials affecting stress distribution around dental implants using three-dimensional finite element analysis (FEA). The study was carried out in the Department of Prosthodontics, Himachal Institute of Dental Sciences, in collaboration with Creo Laboratory, Chennai.

Study Design and Software Tools

The investigation employed 3D finite element modeling, a technique that breaks down complex structures into small, manageable elements connected at nodes. This approach allows for accurate simulation of stress and strain within a system. A geometric model representing the mandibular first premolar region was developed using a CBCT-derived STL file. To simplify the modeling, the mandibular canal was excluded.

The modeling process involved several software tools:

- **Slicer software**: Converted CBCT (DICOM) files into STL format.
- **SpaceClaim**: Imported and refined the STL model.
- **ANSYS 2023**: Used for meshing, material assignment, and stress simulation.
- **Pro/ENGINEER**: Assisted in constructing the 3D CAD models.

Model Construction

A mandibular segment with Type II bone quality was chosen, featuring a 2 mm cortical bone layer surrounding cancellous bone. Six models were created, each including a single implant and crown with varying CIRs and materials:

- **Implant**: A 4.0 mm × 10 mm Osstem implant with internal hex connection.
- **Abutments**: Custom abutments of three heights—5 mm, 10 mm, and 15 mm—corresponding to crown height spaces (CHS) of 10 mm, 15 mm, and 20 mm.
- **Crowns**: A total of six crowns were designed—three made from PEEK and three from zirconia. Each material group had CHS of 10 mm, 15 mm, and 20 mm, leading to CIRs of 1:1, 1.5:1, and 2:1 respectively. Cement space was standardized at 25 µm.

The models were as follows:

Model	CIR	Crown Material
1	1:1	PEEK
2	1:1	Zirconia
3	1.5:1	PEEK
4	1.5:1	Zirconia
5	2:1	PEEK

Model	CIR	Crown Material
6	2:1	Zirconia

Material Properties

- Each component of the models was assigned mechanical properties based on literature data, assuming materials to be homogeneous, isotropic, and linearly elastic:

Material	Young's Modulus (GPa)	Poisson's Ratio
Cortical Bone	13.7	0.30
Cancellous Bone	1.37	0.30
Titanium (Implant)	110	0.35
Zirconia Crown	210	0.30
PEEK Crown	3.5	0.36

Meshing and Load Application

All models were meshed using the ANSYS preprocessor to create finite elements from the geometry. The mesh was refined to ensure accuracy in stress distribution evaluation. After meshing, the models were analyzed in ANSYS Workbench.

Loads were applied to mimic masticatory forces:

- **Vertical load**: 200 N
- **Oblique load**: 100 N at a 45° angle

These forces were applied to the lingual cusp of the crown to simulate functional loading.

Evaluation

Post-processing analysis was performed using ANSYS software. Stress distribution was observed in the following components:

- Crown
- Abutment
- Screw
- Implant body
- Surrounding bone

Stress magnitudes were visualized using color mapping: red indicated high stress areas, while blue showed low-stress regions. These visualizations helped identify how different materials and CIRs influenced the stress levels at each component.

Assumptions

Several standardized assumptions were made for simulation:

- All materials were treated as isotropic, homogeneous, and linearly elastic.
- Complete osseointegration between implant and bone was assumed.

III. RESULTS AND OBSERVATIONS

Table 1 showing Von Mises Stress Values (MPa) Under Vertical Load

Length	Material	Bone	Implant Neck	Abutment	Abutment Screw	Crown
10 mm	PEEK	24.22	36.565	34.915	21.239	8.149
10 mm	Zirconia	24.22	36.565	34.915	21.239	8.149
15 mm	PEEK	41.971	48.565	28.398	27.775	5.1665
15 mm	Zirconia	41.974	48.565	28.398	27.774	17.746
20 mm	PEEK	27.801	60.59	28.023	27.346	6.09
20 mm	Zirconia	27.798	60.565	27.595	27.348	17.337

International Journal Dental and Medical Sciences Research
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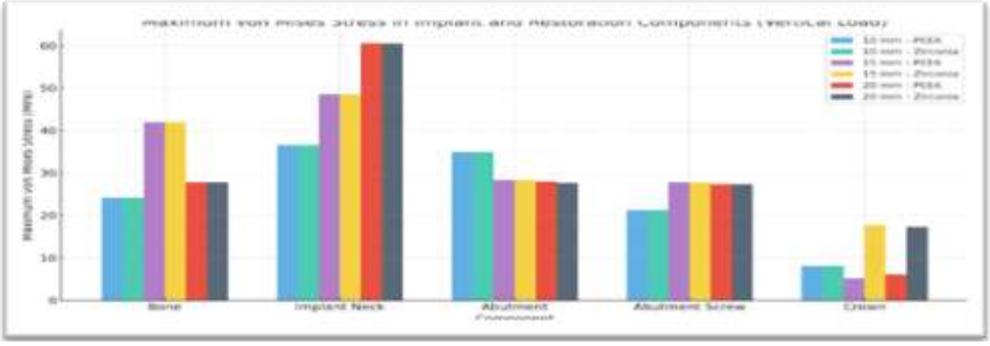
Table 2 showing Von Mises Stress Values (MPa) Under Oblique Load

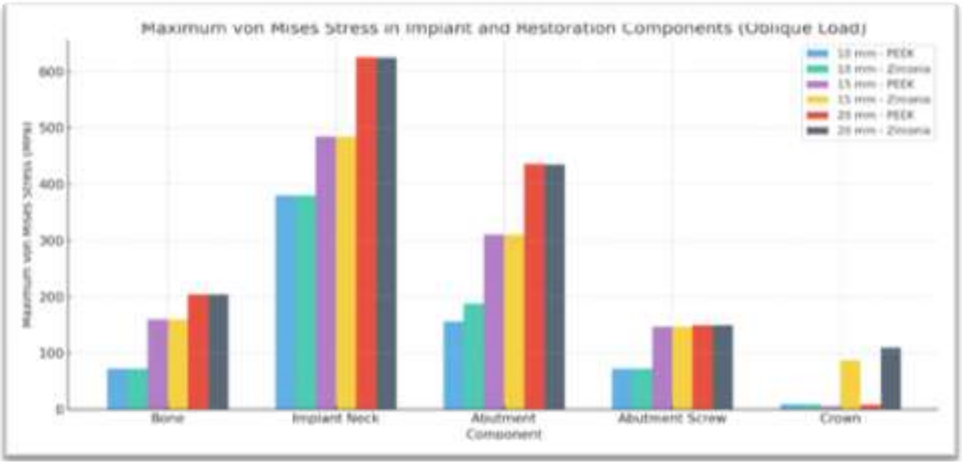
Length	Material	Bone	Implant Neck	Abutment	Abutment Screw	Crown
10 mm	PEEK	71.82	379.56	156.285	72.435	8.605
10 mm	Zirconia	71.82	379.56	187.97	72.435	8.605
15 mm	PEEK	160	484.52	310.62	146.49	5.6276
15 mm	Zirconia	159.98	484.48	310.45	146.58	87.38
20 mm	PEEK	204.68	625.04	435.49	149.69	7.792
20 mm	Zirconia	204.53	624.64	435.04	149.15	109.63

This study evaluated the stress distribution around Osstem implants (4 mm width, 10 mm length) restored with zirconia and PEEK crowns, using different crown-to-implant (C/I) ratios (1:1, 1.5:1, and 2:1), under vertical (200 N) and oblique (100 N) loading. Finite Element Analysis (FEA) was used to assess Von Mises stress values in various implant components and peri-implant bone.



Graph 1 showing Maximum von mises stress (MPa) under vertical load in C/I ratio of 1:1, 1.5:1, 2:1 PEEK and Zirconia crown in

- Bone
- Implant
- Abutment
- Abutment screw
- Crown



Graph 2 showing Maximum von mises stress (MPa) under oblique load in C/I ratio of 1:1, 1.5:1, 2:1 PEEK and Zirconia crown in

- Bone
- Implant
- Abutment
- Abutment screw
- Crown

1. **Stress Distribution in Bone**

Vonmises stress under oblique load was almost three times, four times and seven time than those under vertical load.

- Vertical Loading

Von mises stress value in bone observed in C/Iratio 1:1, 1.5:1 and 2:1 were 24.22 MPa, 41.971 MPa and 27.8 MPa, respectively under vertical load in both PEEK and zirconia models (Table 1).Stress in bone remained relatively moderate under vertical loading across all groups.The highest stress values were observed in the C/I ratio 1.5:1, with both zirconia (Fig 4E) and PEEK model (Fig 3E) showing 41.97 MPa. The C/I ratio 1:1 (Fig 1E,2E) and 2:1 (Fig 5E,6E) showed relatively lower stress in bone, suggesting a non-linear relationship between C/I ratio and bone stress under vertical loading. Stress was concentrated in the crestal region and the bone implant interface. Stress of around 15.99 MPa was seen in the apical portion of implant in PEEK restored prosthesis irrespective of the crown implant ratio.

- Oblique Loading:

Von mises stress value in bone observed in C/I ratio 1:1, 1.5:1 and 2:1 were 71.82 MPa, 160MPaand 204MPa ,respectively under oblique load in both PEEK and zirconia model (Table 2). Oblique forces resulted in a substantial increase in stress in the bone, particularly in groups with higher C/I ratios. Stress values increased from 71.82 MPa to 204.68 MPa for PEEK model in C/I ratio of 1:1(Fig 1K) and 2:1(Fig 5K), and similarly for zirconia model (Fig 2K, 6K). C/Iratio of 1.5:1 reported the stress of around 160MPa approximately for both PEEK (Fig 3K) and zirconia model (Fig 4K).This suggests that increased crown height leads to moretorque and stress transmission to the bone.

Cortical bone exhibited the highest stress concentration, particularly in the 1.5:1 (160MPa) and 2:1 C/I ratios (204.68 MPa). Stress was more concentrated in bone implant interface and crestal region more concentrated in the buccal region opposite to the side of load applied. Little difference in stress concentration was seen betweenPEEK and zirconia model in higher ratios. PEEK model showed more stress concentration than zirconia model though the difference was negligible.

Cancellous bone showed minimal stress values across all configurations (10 to 17MPa), indicating its lower role in load bearing compared to cortical bone.

2. Stress distribution in Implant

In implant, von mises stress in the C/I ratios 1:1,1.5:1 and 2:1 under oblique load were almost ten times higher than those under vertical load.

- Under **vertical loading**, implant neck stress increased with C/I ratio, from 36.56 MPa(C/I ratio 1:1)(Fig 1F, 2F) to 60.59 MPa(C/I ratio 2:1) (Fig 5F, 6F). C/I ratio 1.5:1 reported stress of 484MPaapproximately for both PEEK (Fig 3F) and zirconia model (Fig 4F). The difference between zirconia and PEEK was negligible here. Even stress distribution was seen in all the models. (Table1, Graph1)
- Under **oblique loading**, stress values in implant neck increased drastically with risingC/Iratio, peaking at 625.04MPa (C/I2:1, PEEK model)(Fig5L)and624.64 MPa (C/I2:1, zirconia model) (Fig 6L). Stress values in C/I ratio1:1and1.5:1were around 379 MPa and 485M Pain both PEEK (Fig 1L, 3L) and Zirconia (Fig 2L, 4L). (Table 2, Graph 2)

This indicates that the **implant collar and neck are primary stress concentration zones**, especially under oblique forces and higher prosthetic heights.

3. Stress distribution in Abutment

In abutment, von mises stress in the C/I ratios 1:1, 1.5: 1 and 2:1 under oblique load were almost four times, ten times and fifteen times higher than those under vertical load.

In **vertical loading**, stress in abutment remained moderate (28–35 MPa) across all groups, with slightly lower values in PEEK groups (Fig 1C,3C,5C) compared to zirconia (Fig 2C,4C,6C). However, C/I ratio 1:1 showed highest Von mises stress among i.e 34.91MPa than C/I ratio 1.5:1 and 2:1. (Table 1, Graph 1)

However, under **oblique loading**, stress levels sharply increased: For PEEK model (Fig 1I, 3I, 5I): from 156.28 MPa (C/I ratio 1:1) to 435.49 MPa (C/I ratio 2:1). For Zirconia model (Fig 2I, 4I, 6I): from 187.97 MPa (C/I ratio 1:1) to 435.04 MPa (C/I ratio 2:1). Difference of 31.69 MPa was observed in PEEK and zirconiamodel in 1:1 C/I ratio. (Table 2, Graph 2). The abutment-implant connection and abutment neck region showed critical stress buildup, particularly in higher crown height groups.

4. Stress distribution in abutment screw

In abutment screw, von mises stress in the ratios 1:1, 1.5:1 and 2:1 under oblique load were almost three to five times higher than those under

International Journal Dental and Medical Sciences Research
Volume 7, Issue 5, Sept – Oct 2025 pp 132-159 www.ijdmsrjournal.com ISSN: 2582-6018

vertical load.

Under vertical load, the abutment screw experienced relatively stable stress values (21–27 MPa) in both PEEK and Zirconia models. Stress distribution was more in the middle portion of the screw (Fig 1D, 2D, 3D, 4D, 5D, 6D) (Table 1, Graph 1).

Under oblique load, screw stress increased with C/I ratio, peaking at 149.69 MPa (PEEK model) (Fig 5J) and 149.15 MPa (zirconia model) (Fig 6J) in the 2:1 group. C/I ratios 1:1 and 1.5:1 observed stress of 72.44 MPa and 146.5 MPa in both PEEK (Fig 1J, 3J) and Zirconia model (Fig 2J, 4J). The increase was not as steep as that seen in the implant neck or abutment, indicating that while the screw is affected, it is less critical in terms of maximum stress (Table 2, Graph 2).

5. Stress distribution in Crown

In PEEK Crown, vonmises stress in the ratios1:1,1.5:1 and 2:1 under oblique load were almost same than those under vertical load.In Zirconia Crown, von mises stress in the ratios 1:1,1.5:1 and 2:1 under oblique load were almost same, five times and seven times higher than those under vertical load.

- **Under vertical loading**, zirconia crowns consistently showed higher stress values than PEEK crowns in higher ratios exceptin C/I ratio1:1 which depicted stress of 8.149 M Pain both PEEK and zirconia crown. In the1.5:1 C/Iratio, zirconiacrown stress was 17.74 MPa, whereas PEEK was only 5.17 MPa (Fig 3B,4B). In the 2:1 mm group, zirconia showed 17.33 MPa, compared to 6.09 MPa in PEEK (Fig 5B, 6B).This is expected due to zirconia's higher elastic modulus, causing it to abs or band reflect more force at the cervical region, rather than distributing it downward (Table 1, Graph 1).
  - o **Under oblique load,** zirconia crowns again showed significantly higher stress value than PEEK crowns in higher ratios except in C/I ratio 1:1 which depicted stress of 8.149 MPa in both PEEK and zirconia crown. At C/I ratio 2:1, zirconia crown stress was 109.63 MPa (Fig 6H), while PEEK was 7.79 MPa (Fig 5H). Zirconiacrown showedhigher stressesthanpeek crownbutthestress generatedon the implant and abutment were almost same in both materials. (Table 2, Graph 2)

Overall Observations

- Higher crown-to-implant ratios consistently showed increased stress in all components, especially under oblique loading.
- Stress was most concentrated in the implant collar/neck and first thread region, confirming that these are critical areas for implant biomechanical stability.
- The crestal cortical bone showed significantly higher stress in C/I ratio 1.5:1 and 2:1 ratio, especially under lateral forces. Von mises stress value in the alveolar crest surpasses the elasticity of the bone, it may causes micro cracks in the bone and may lead to marginal bone loss under the oblique load.
- The abutment-implant interface and abutment screw also became increasingly vulnerable with rising C/I ratios and oblique forces, warranting careful consideration during prosthetic planning.
- Zirconia and PEEK crown showed major differences in stress concentration but the transfer of stress on bone and implant was almost same.

PEEK(1:1)

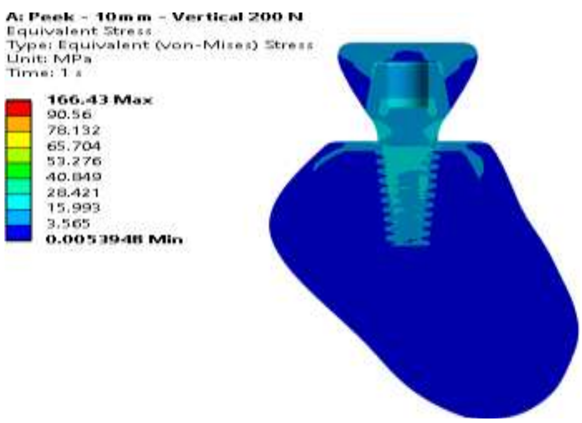


Figure1A showing stresses overall

ZIRCONIA(1:1)

Figure2A showing stresses overall

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Volume 7, Issue 5, Sept – Oct 2025 pp 132-159 www.ijdmsrjournal.com ISSN: 2582-6018

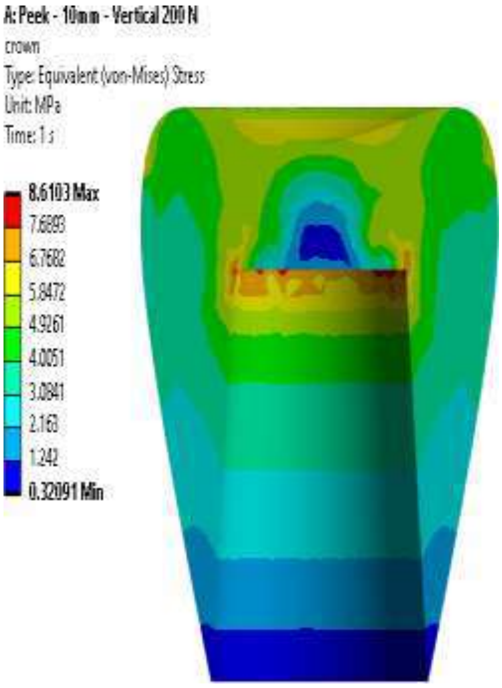


Figure1B showing stresses in crown region

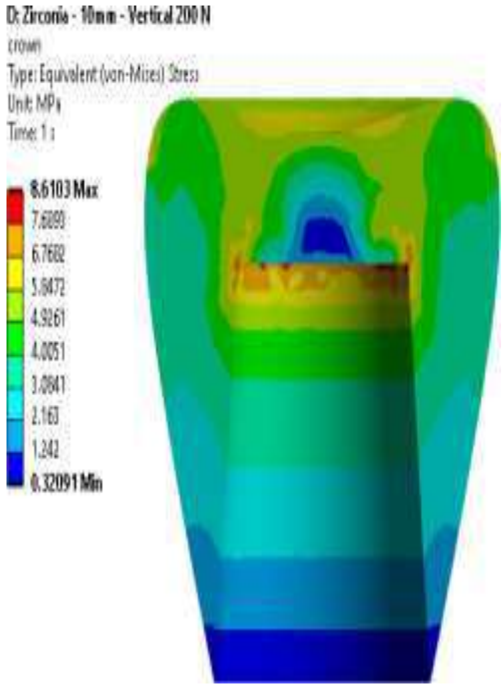


Figure2B showing stresses in crown region

PEEK(1:1) **ZIRCONIA(1:1)**

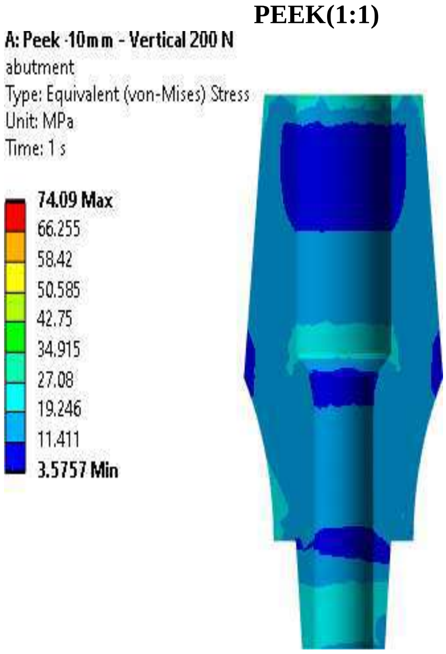


Figure1C showing stresses in abutment

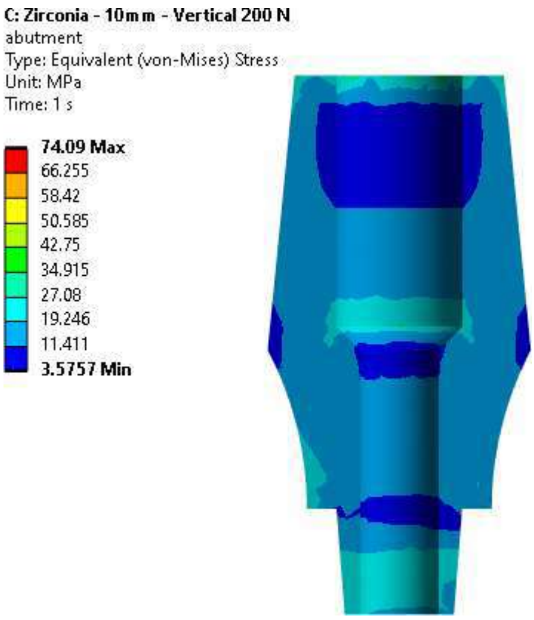
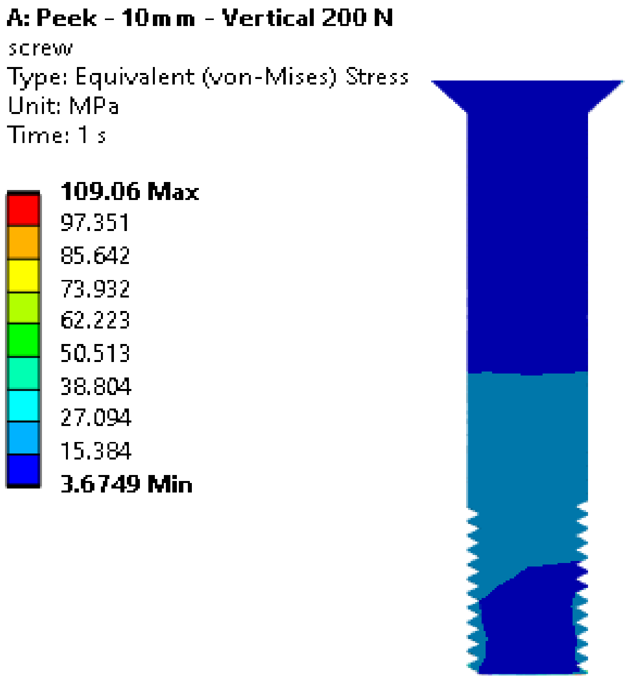


Figure2C showing stresses in abutment

International Journal Dental and Medical Sciences Research
Volume 7, Issue 5, Sept – Oct 2025 pp 132-159 www.ijdmsrjournal.com ISSN: 2582-6018



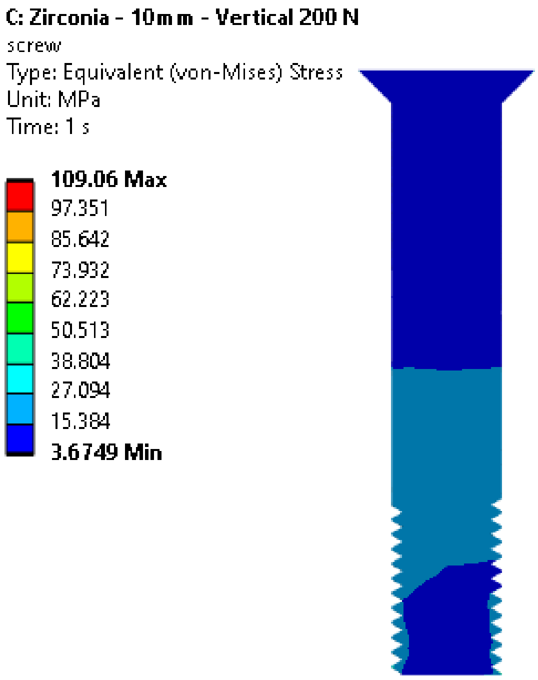
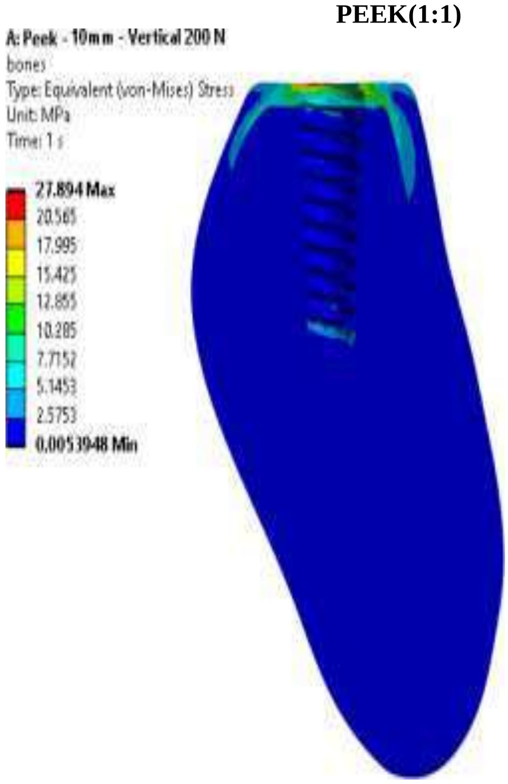


Figure1D showing stresses in abutments crew PEEK(1:1)

Figure 2D showing stresses in abutment screw ZIRCONIA(1:1)



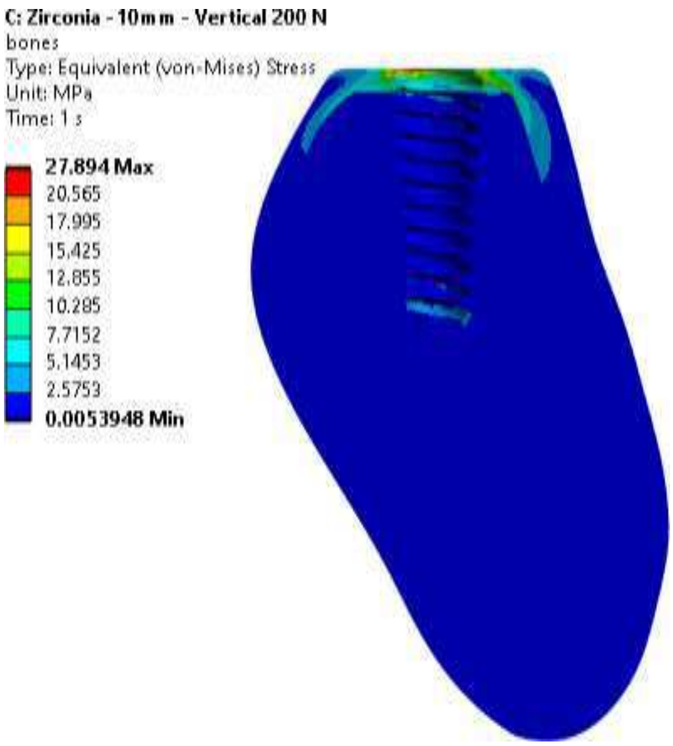


Figure1E showing stresses in bone

Figure 2E showing stresses in bone

International Journal Dental and Medical Sciences Research
Volume 7, Issue 5, Sept – Oct 2025 pp 132-159 www.ijdmsrjournal.com ISSN: 2582-6018

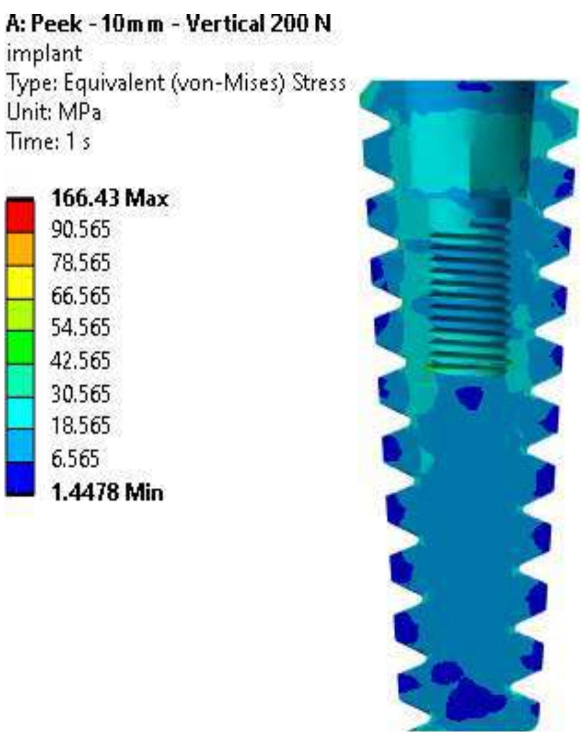


Figure 1F showing stresses in implant

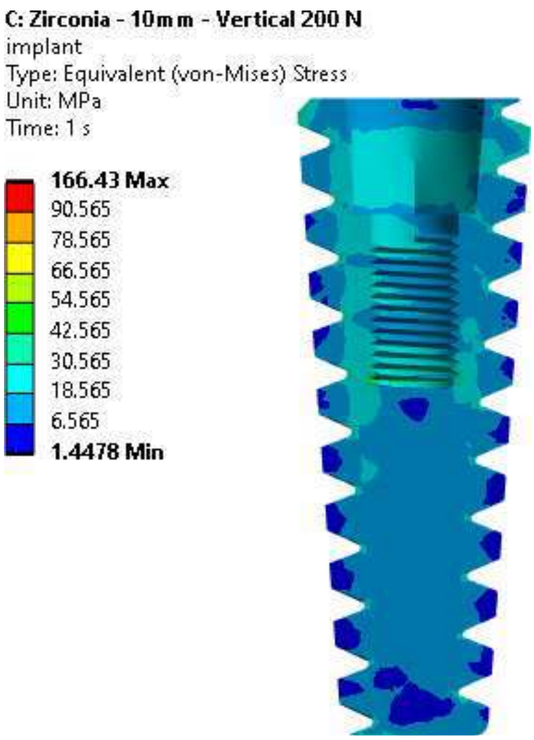


Figure 2F showing stresses in implant

PEEK(1:1)

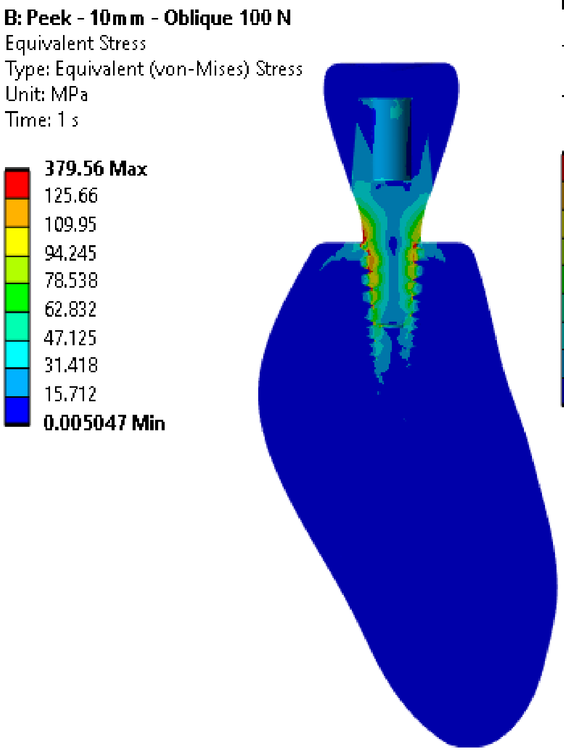


Figure 1G showing stresses overall

ZIRCONIA(1:1)

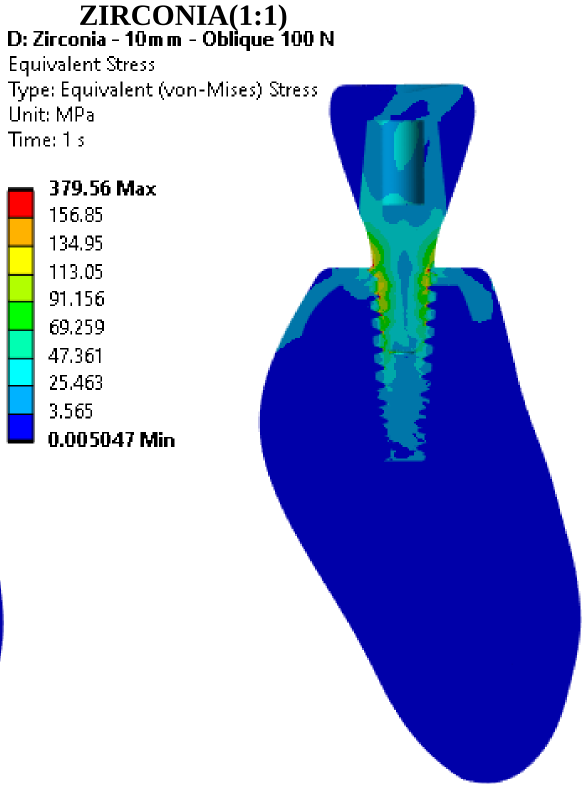


Figure 2G showing stresses overall

International Journal Dental and Medical Sciences Research
Volume 7, Issue 5, Sept – Oct 2025 pp 132-159 www.ijdmsrjournal.com ISSN: 2582-6018

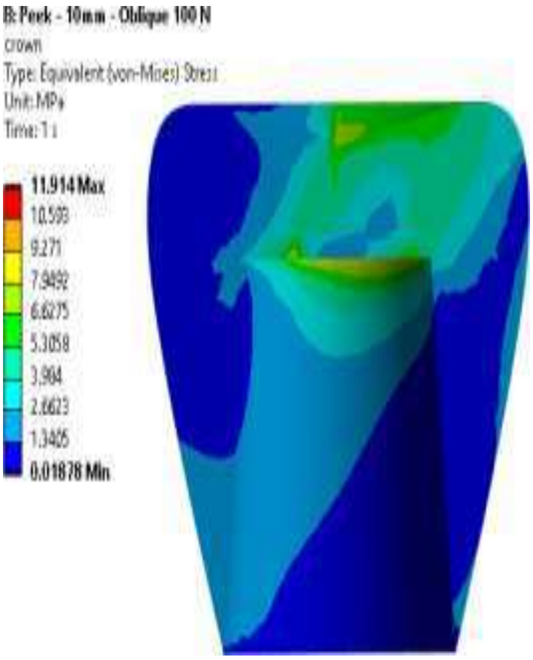


Figure 1H showing stresses in crown region

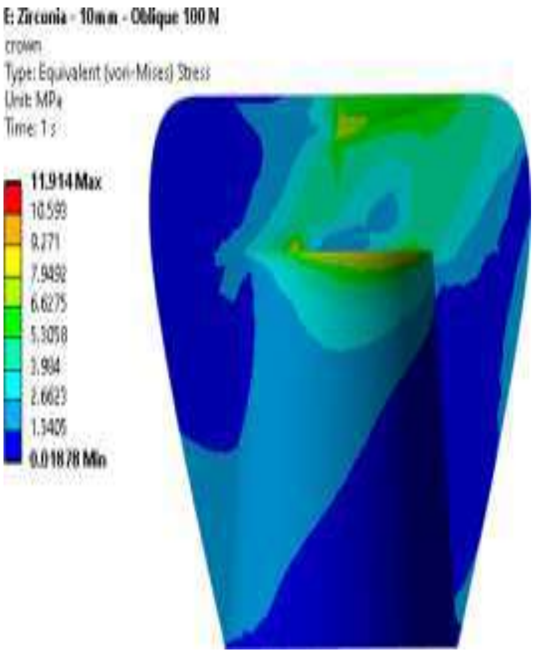


Figure 2H showing stresses in crown region

PEEK(1:1)

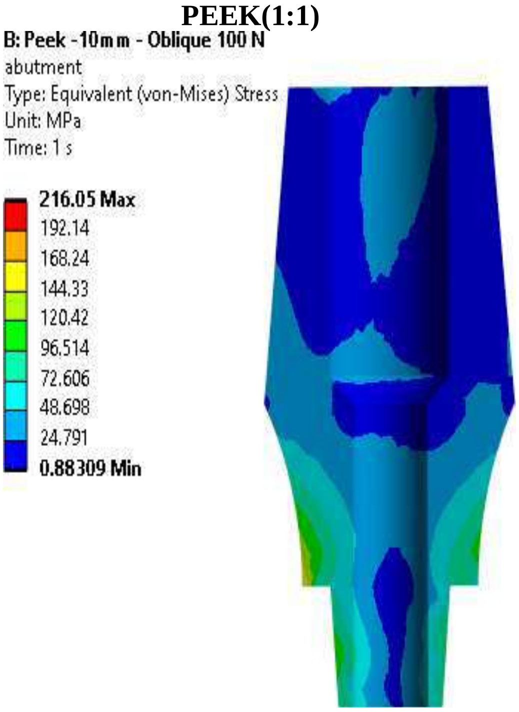


Figure 1I showing stresses in abutment

ZIRCONIA(1:1)

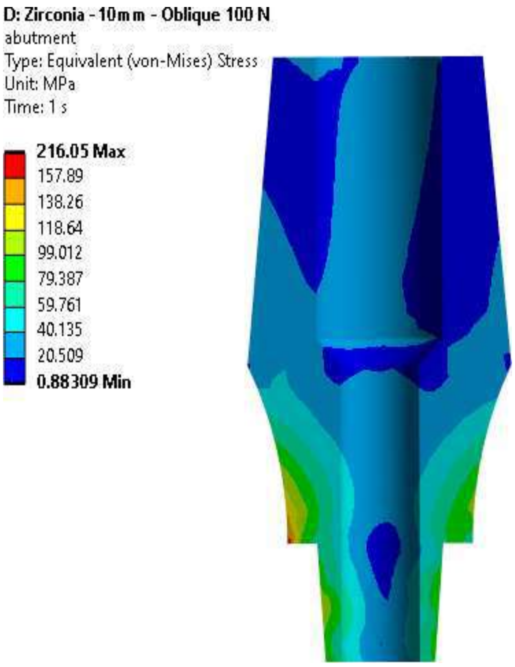


Figure 2I showing stresses in abutment

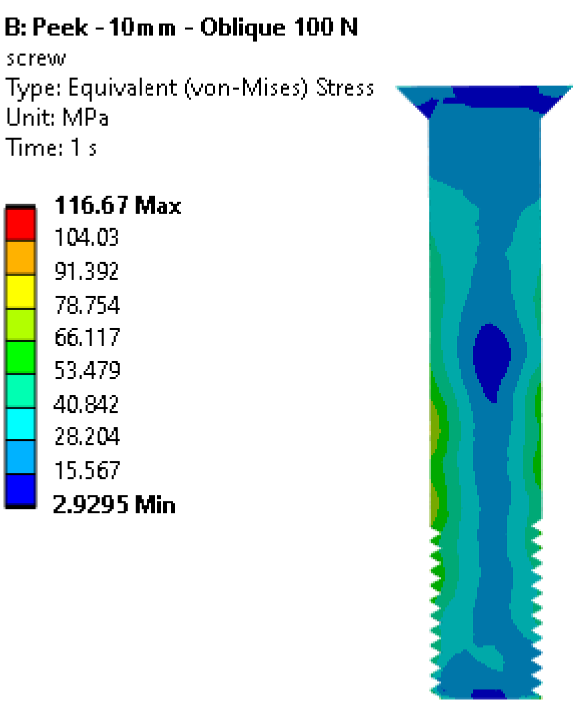


Figure 1J showing stresses in abutment screw

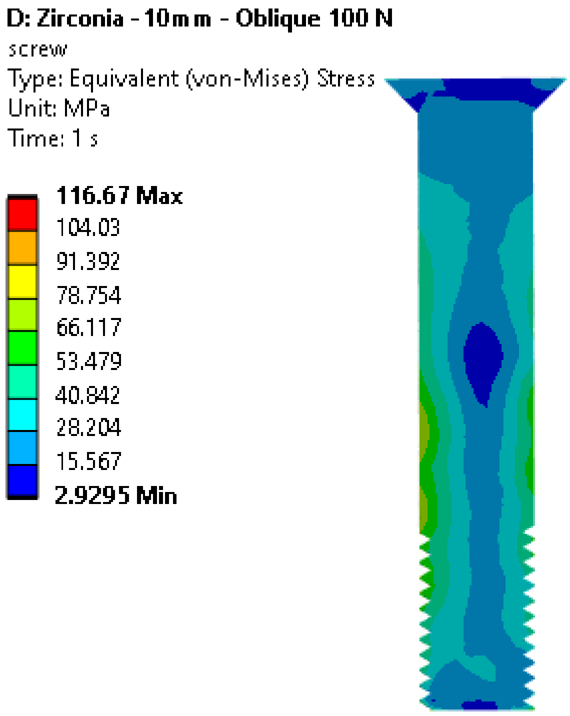


Figure 2J showing stresses in abutment screw

PEEK(1:1)

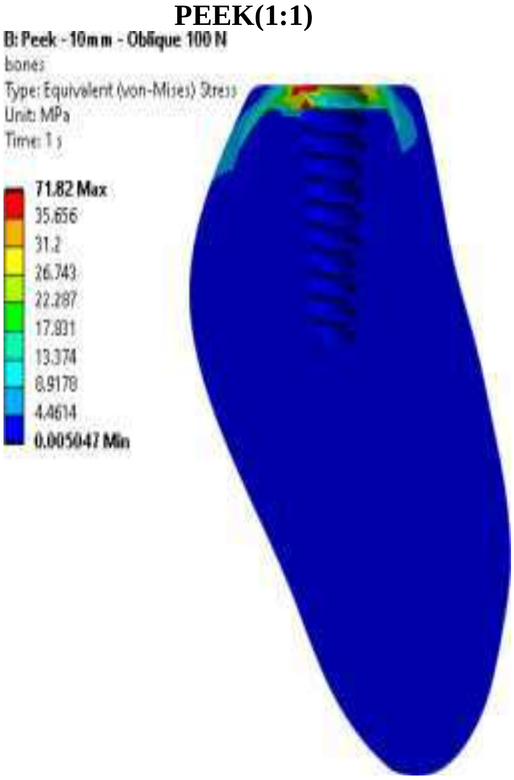


Figure 1K showing stresses in bone

ZIRCONIA(1:1)

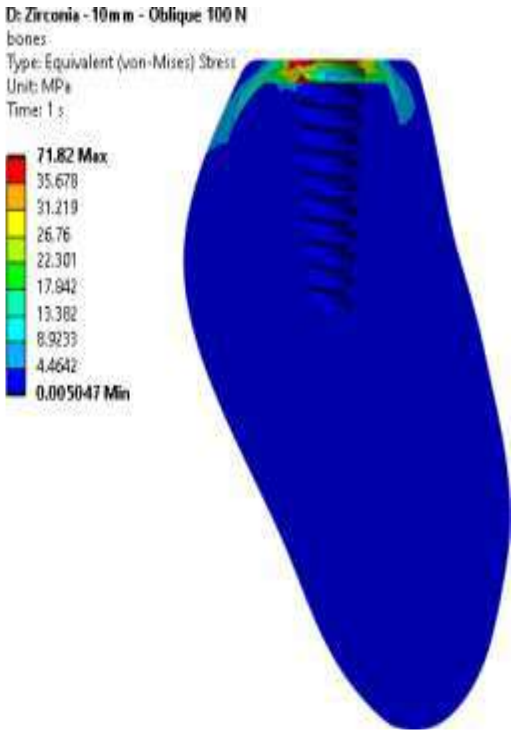


Figure 2K showing stresses in bone

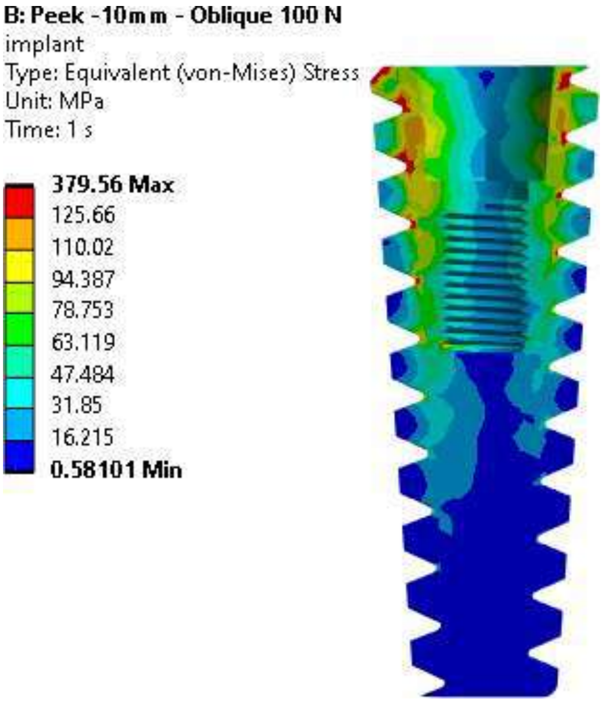


Figure 1L showing stresses in implant

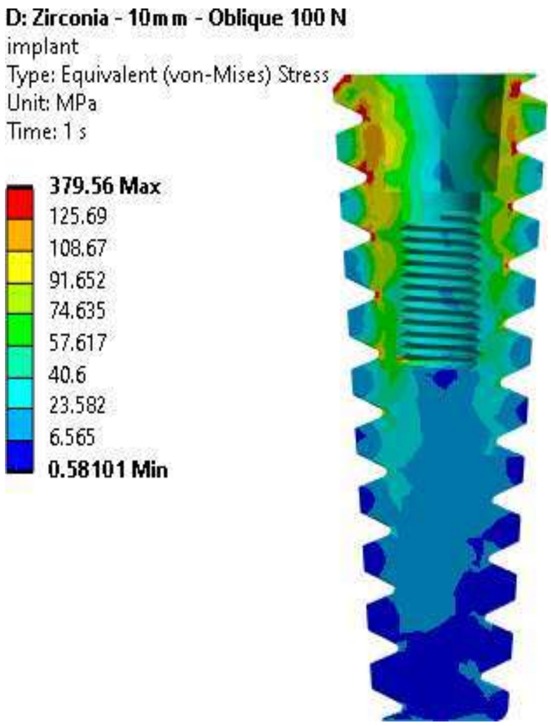


Figure 2L showing stresses in implant

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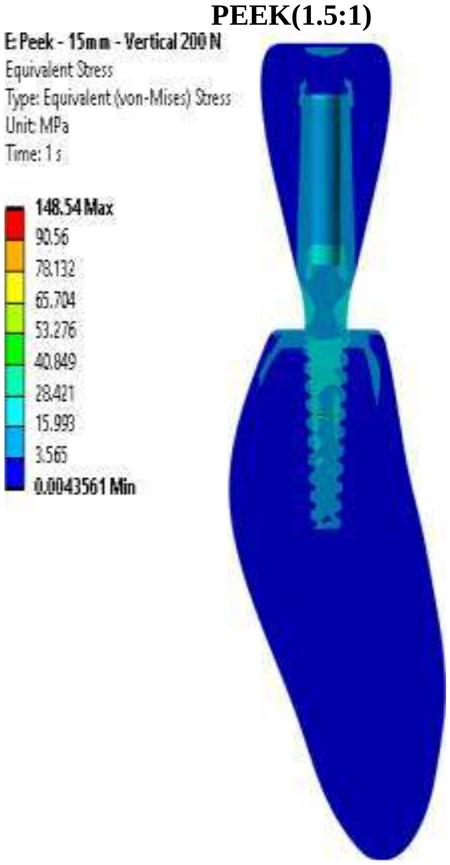
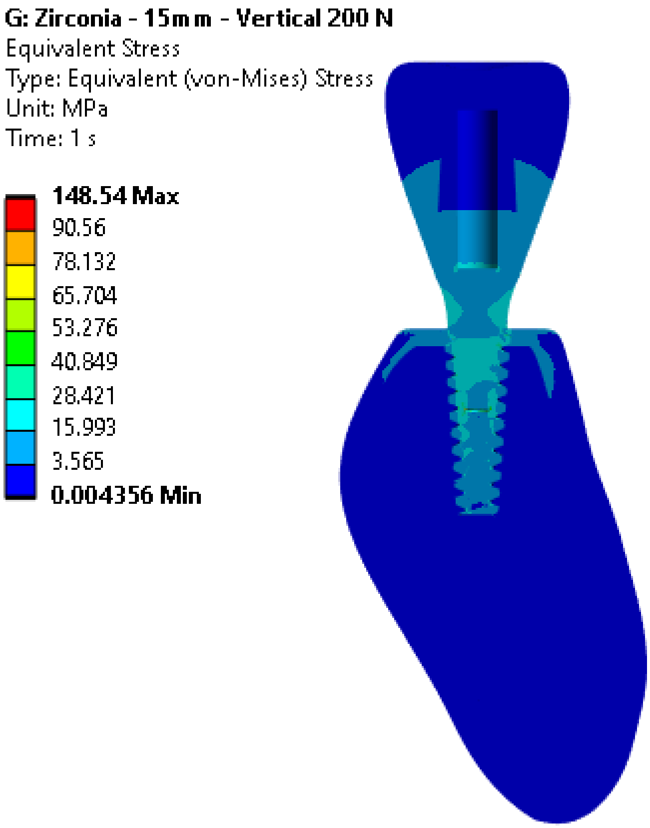


Figure 3A showing stresses overall

ZIRCONIA(1.5:1)



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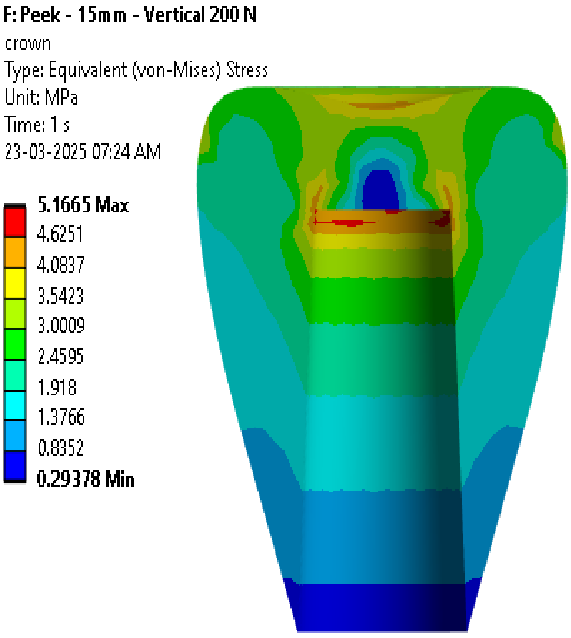

Figure 3B showing stresses in crown

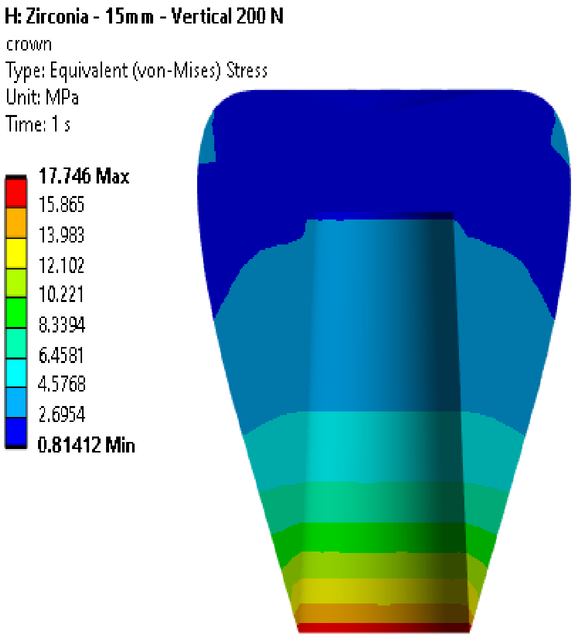

Figure 4B showing stresses in crown

PEEK(1.5:1)

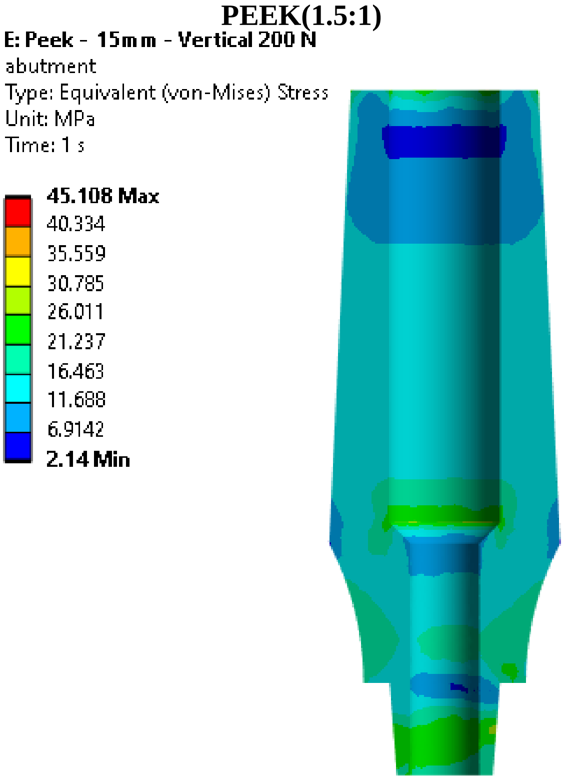

Figure 3C showing stresses in abutment

ZIRCONIA(1.5:1)

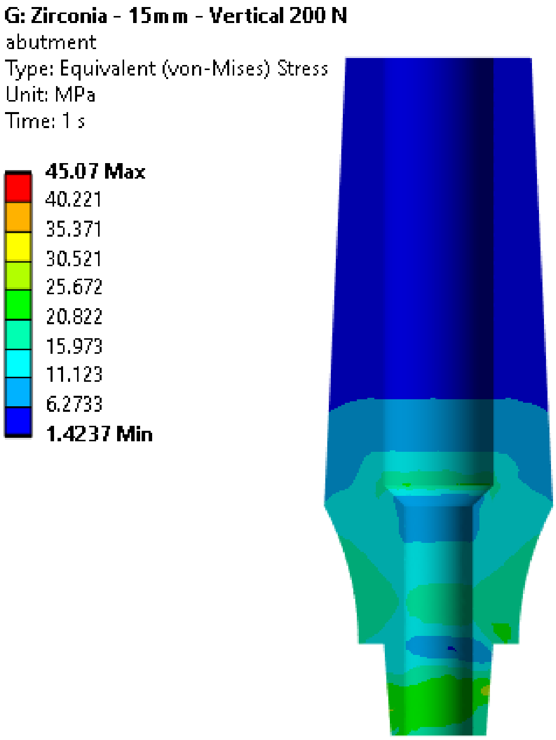

Figure 4C showing stresses in abutment

International Journal Dental and Medical Sciences Research
Volume 7, Issue 5, Sept – Oct 2025 pp 132-159 www.ijdmsrjournal.com ISSN: 2582-6018

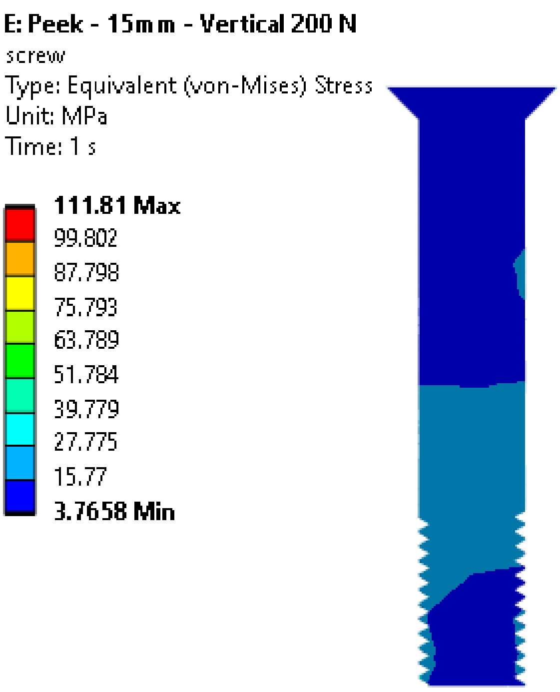

Figure 3D showing stresses in abutments crew

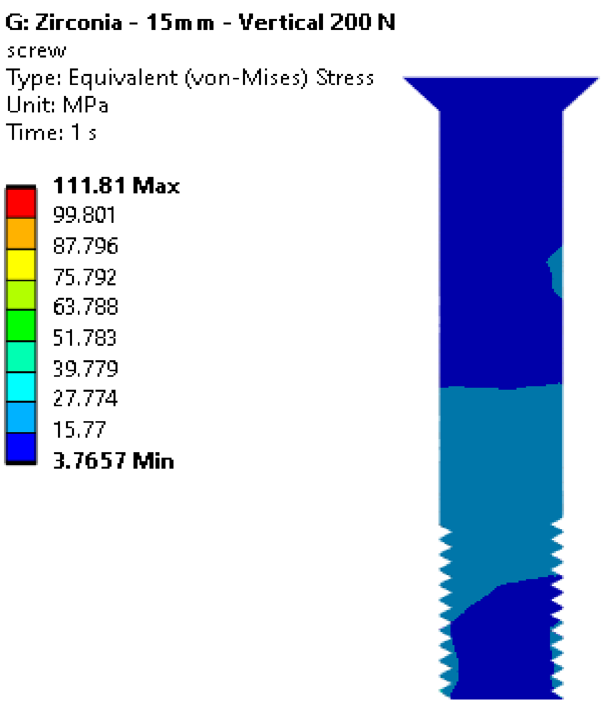

Figure 4D showing stresses in abutments crew

PEEK(1.5:1)

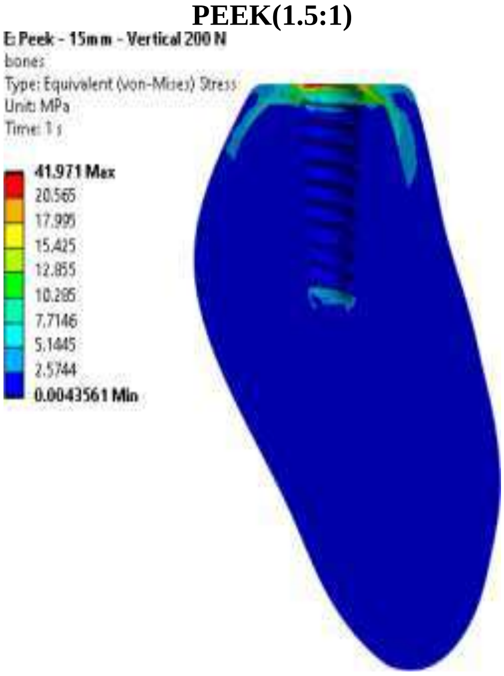

Figure 3E showing stresses in bone

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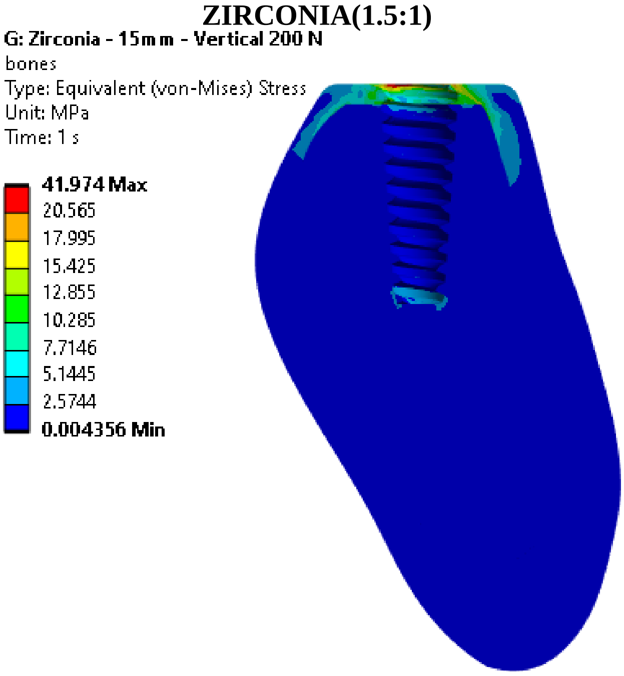


Figure4E showing stresses in bone

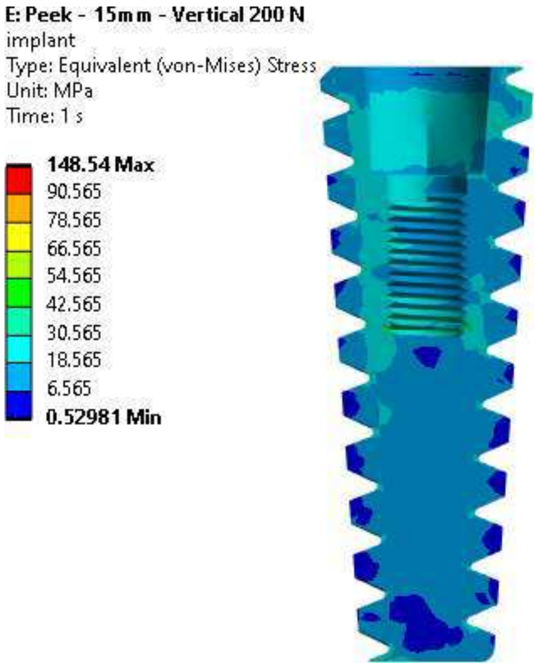
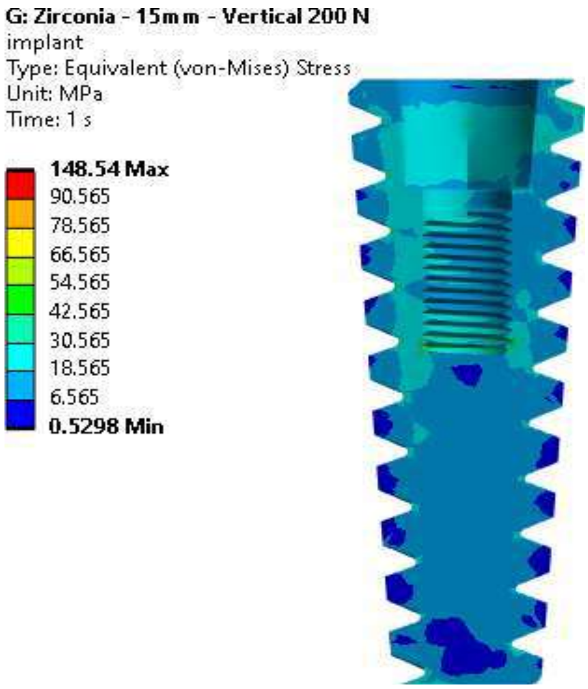


Figure 3F showing stresses in implant



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PEEK(1.5:1)

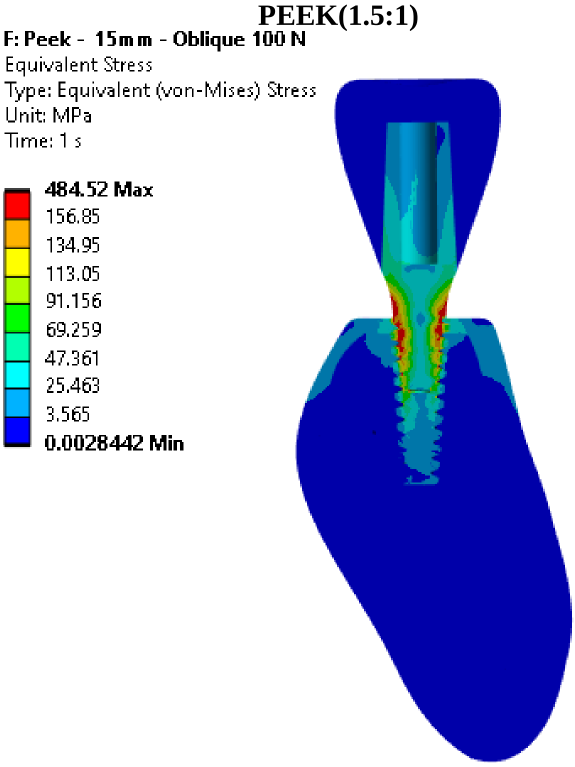

Figure 3G showing stresses overall

ZIRCONIA(1.5:1)

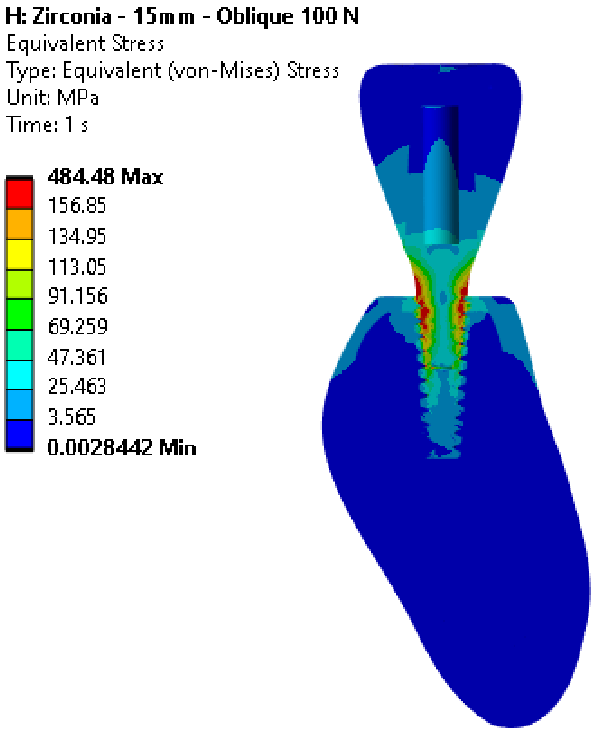

Figure 4G showing stresses overall

International Journal Dental and Medical Sciences Research
Volume 7, Issue 5, Sept – Oct 2025 pp 132-159 www.ijdmsrjournal.com ISSN: 2582-6018

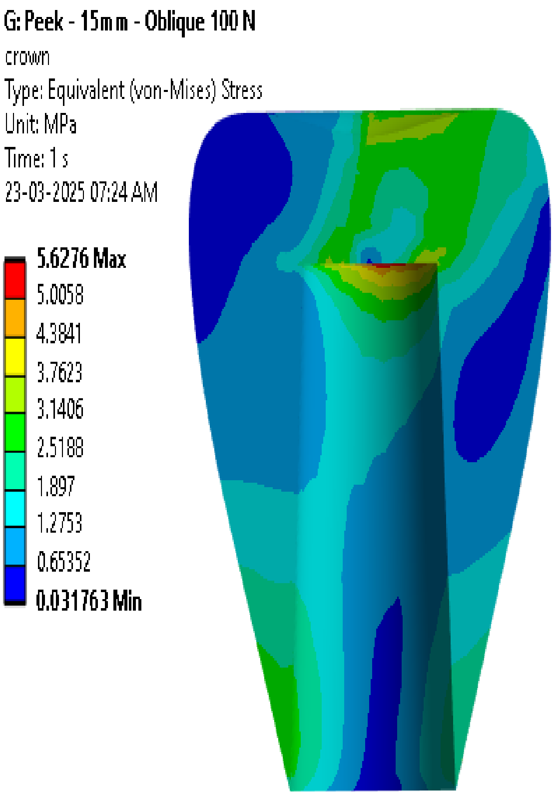

Figure 3H showing stresses in crown

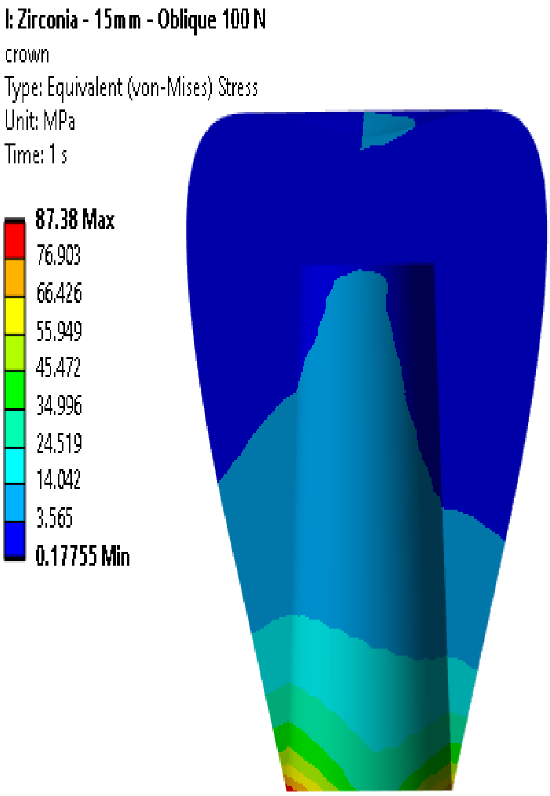

Figure 4H showing stresses in crown

PEEK(1.5:1)

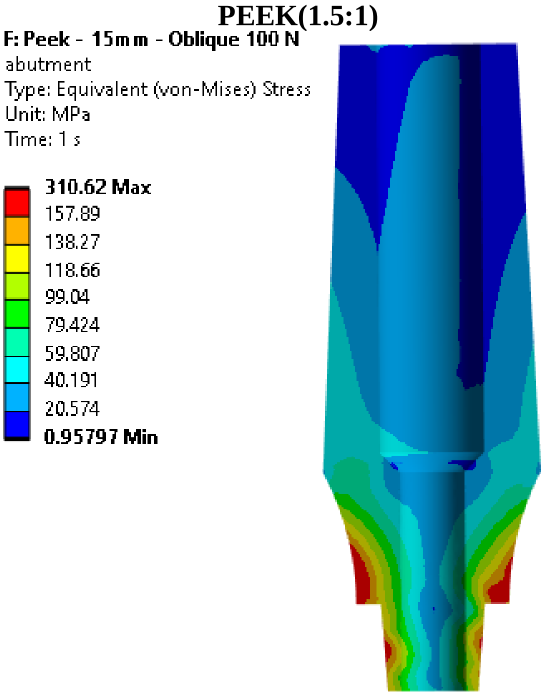

Figure 3I showing stresses in abutment

ZIRCONIA(1.5:1)

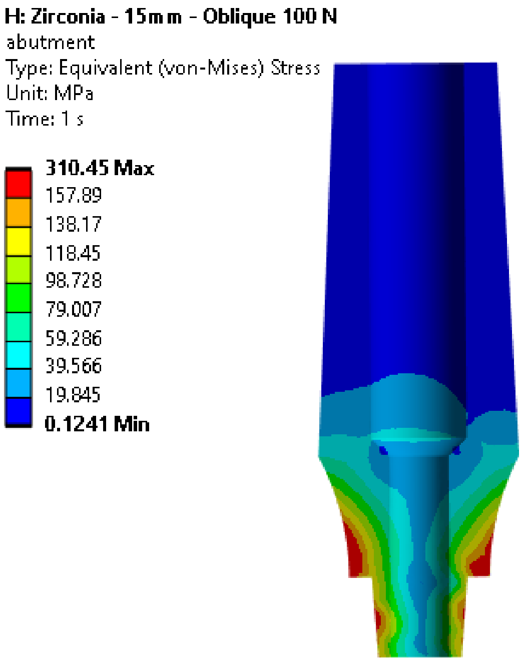

Figure 4I showing stresses in abutment

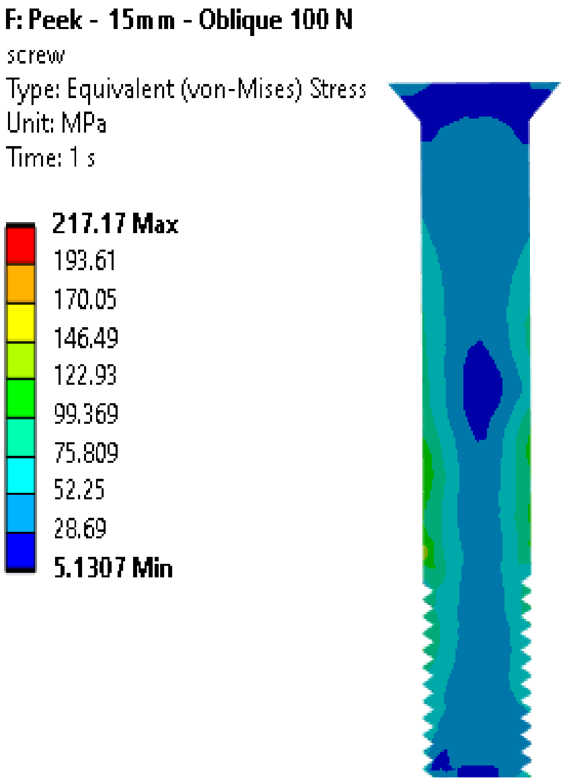

Figure 3J showing stresses in abutments crew

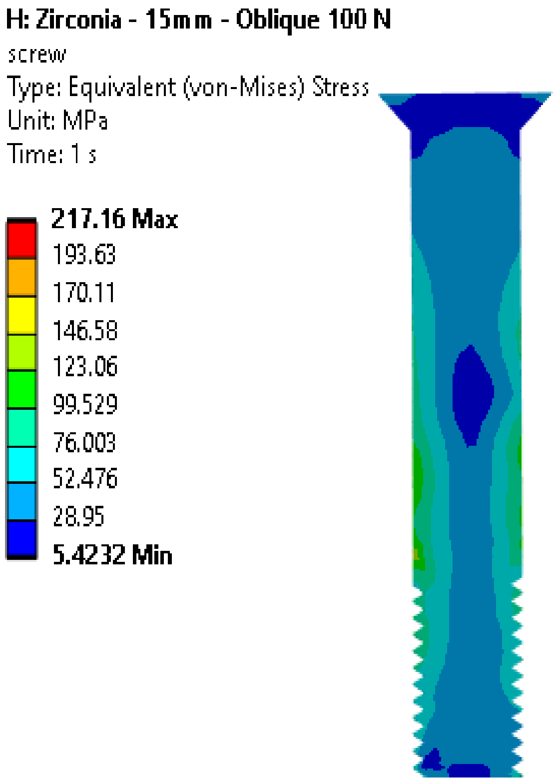

Figure 4J showing stresses in abutments crew

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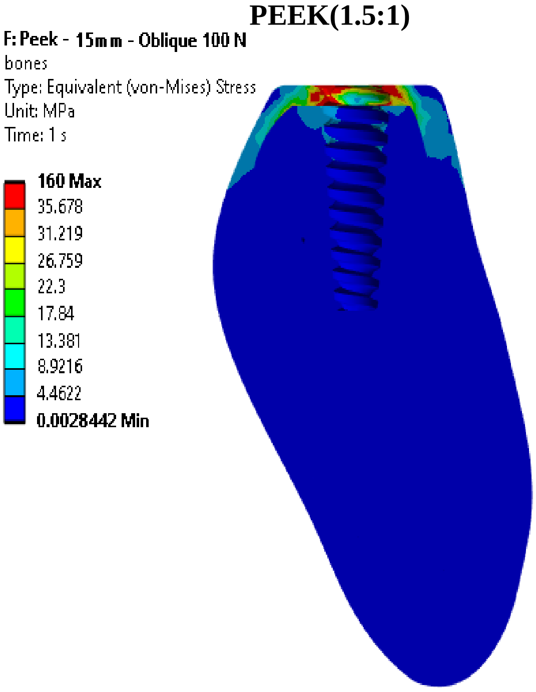


Figure 3K showing stresses in bone

ZIRCONIA(1.5:1)

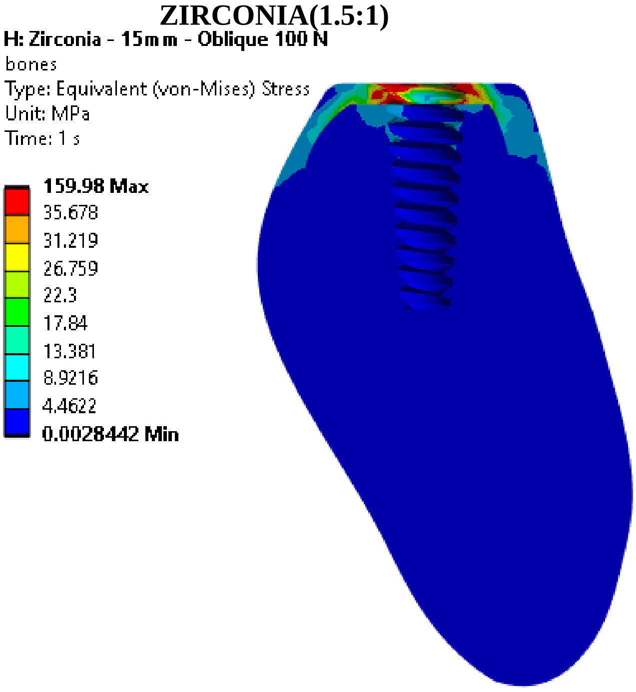
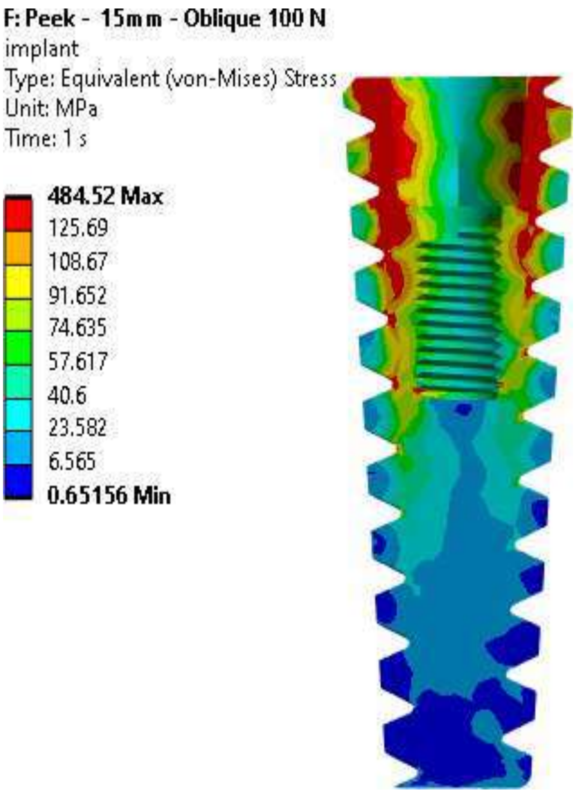


Figure 4K showing stresses in bone

International Journal Dental and Medical Sciences Research
Volume 7, Issue 5, Sept – Oct 2025 pp 132-159 www.ijdmsrjournal.com ISSN: 2582-6018



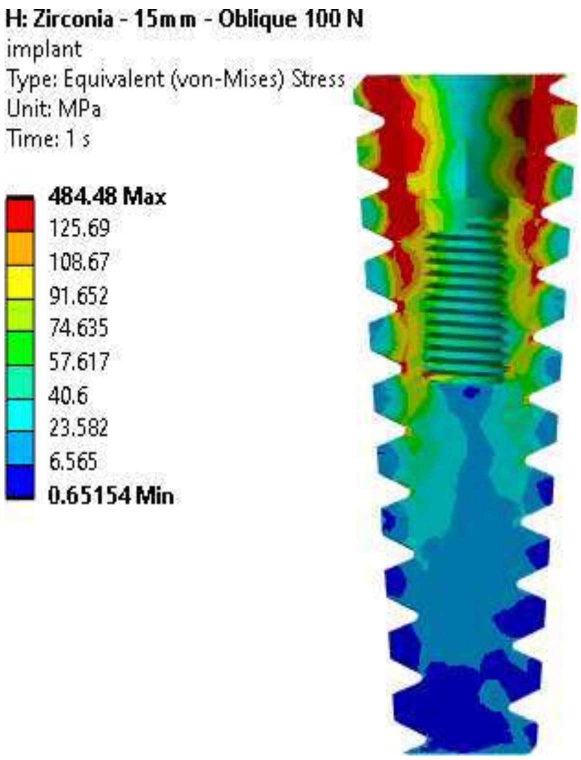
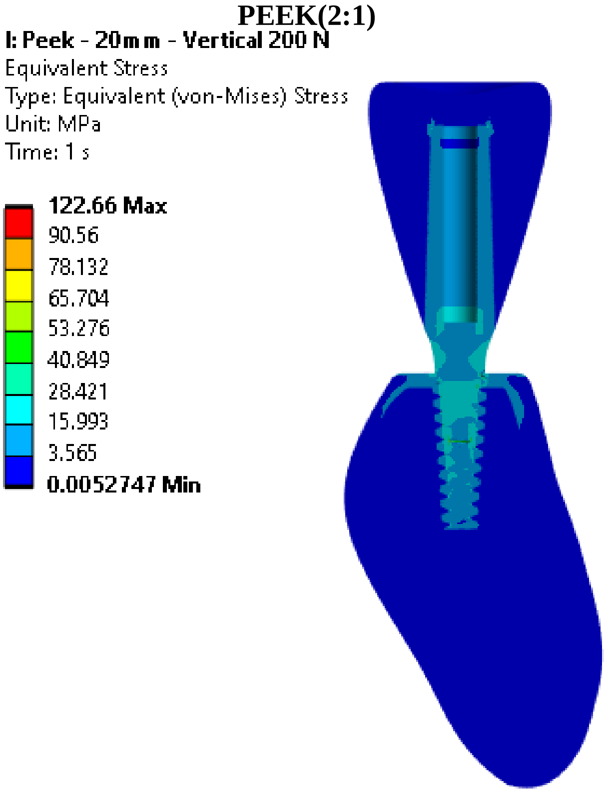


Figure 3L showing stresses in implant **Figure 4L showing stresses in implant**

PEEK(2:1) **ZIRCONIA(2:1)**



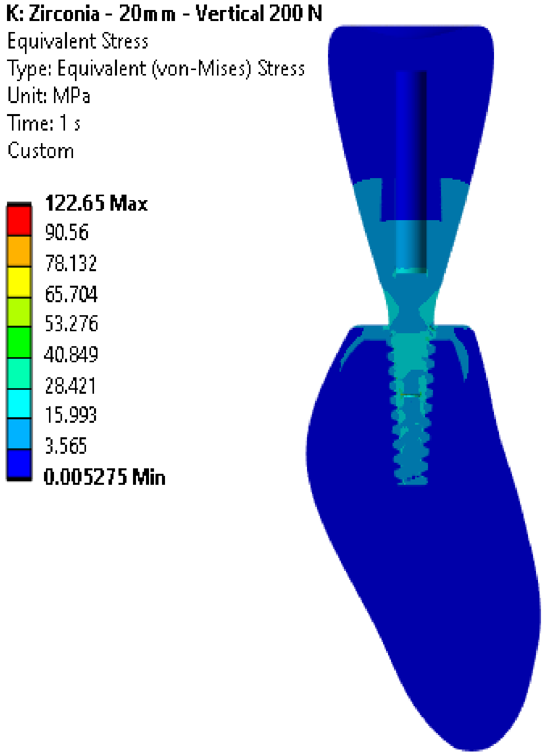


Figure 5A showing stresses overall **Figure 6A showing stresses overall**

International Journal Dental and Medical Sciences Research
Volume 7, Issue 5, Sept – Oct 2025 pp 132-159 www.ijdmsrjournal.com ISSN: 2582-6018

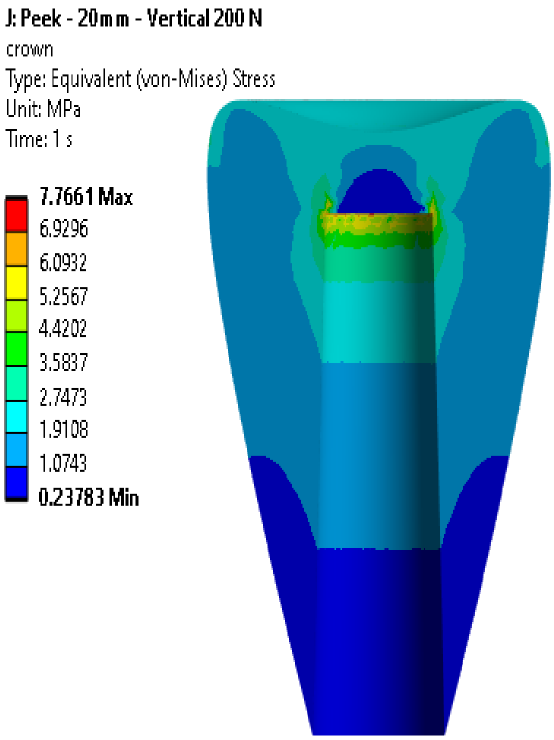


Figure 5B showing stresses in crown

PEEK(2:1)

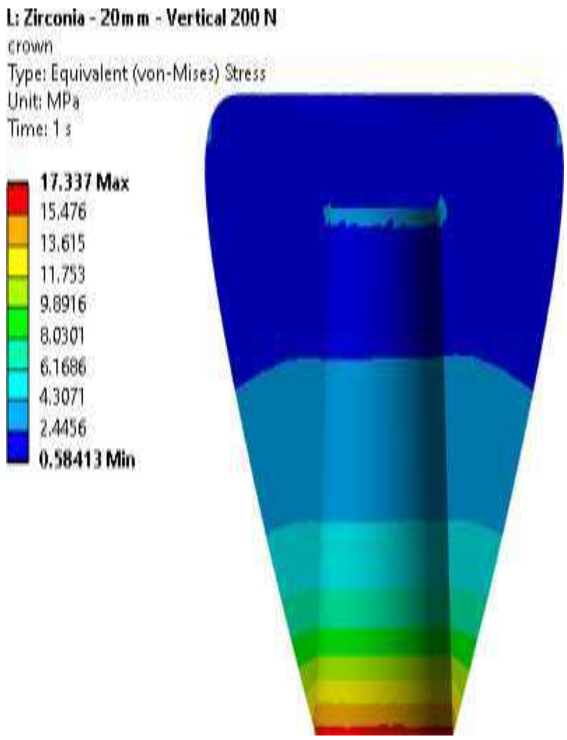


Figure 6B showing stresses in crown

ZIRCONIA(2:1)

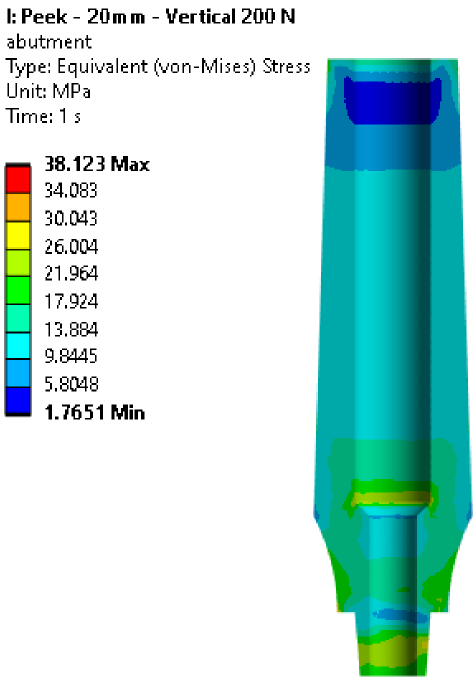


Figure 5C showing stresses in abutment

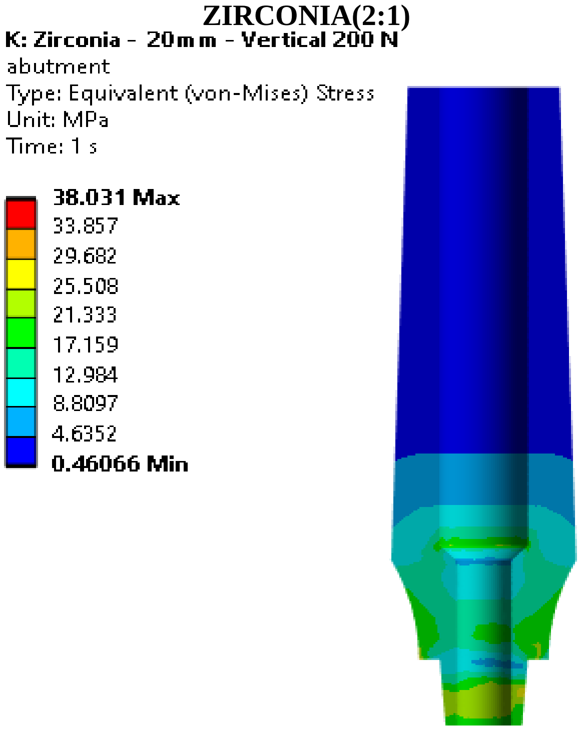
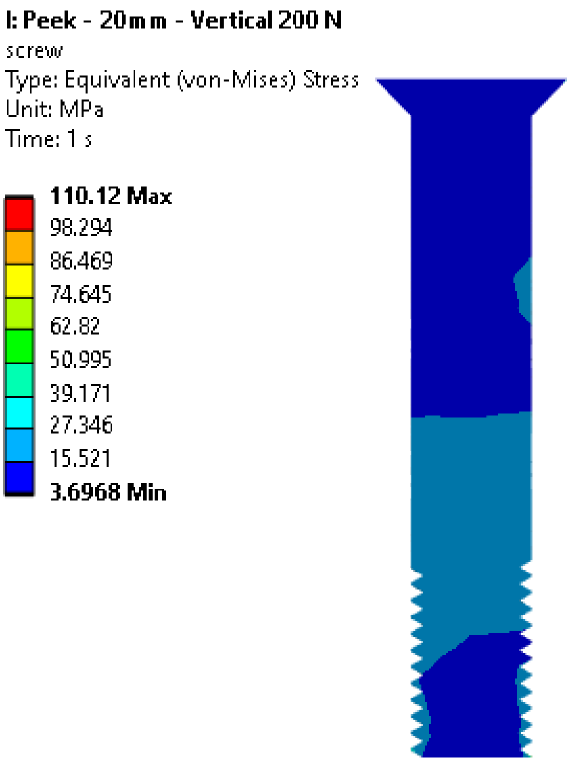


Figure 6C showing stresses in abutment

International Journal Dental and Medical Sciences Research
Volume 7, Issue 5, Sept – Oct 2025 pp 132-159 www.ijdmsrjournal.com ISSN: 2582-6018



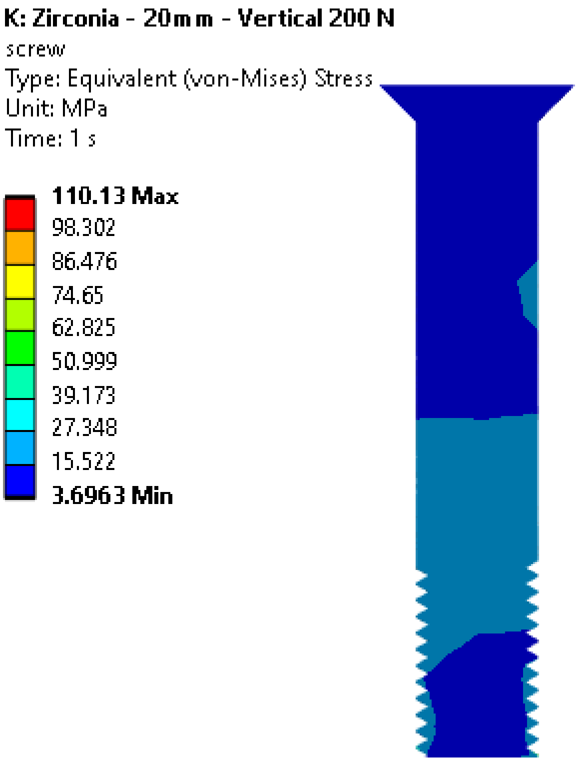
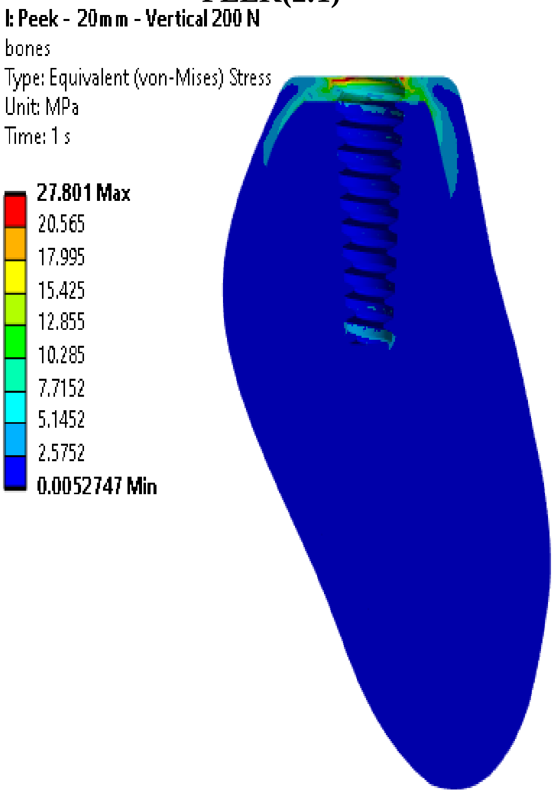


Figure 5D showing stresses in abutment screw Figure6Dshowingstresses in abutment screw

PEEK(2:1) ZIRCONIA(2:1)



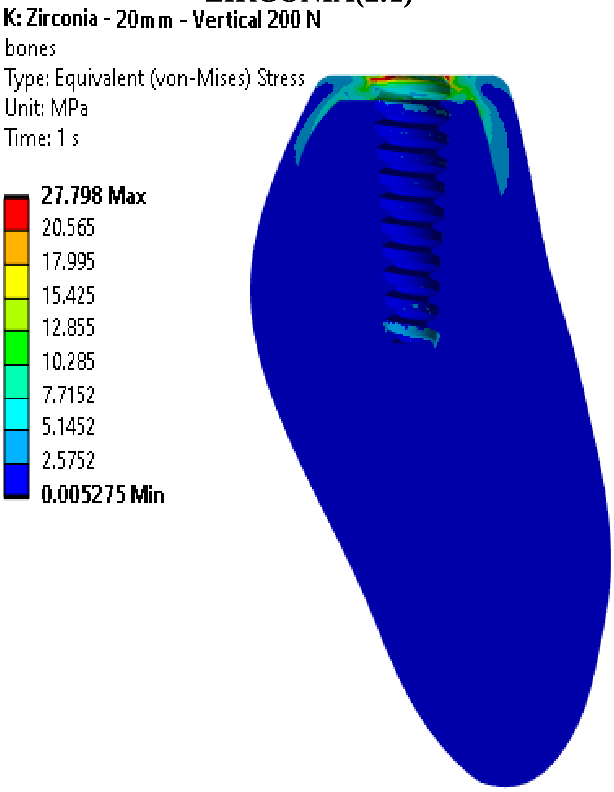


Figure 5E showing stresses in bone Figure 6E showing stresses in bone

International Journal Dental and Medical Sciences Research
Volume 7, Issue 5, Sept – Oct 2025 pp 132-159 www.ijdmsrjournal.com ISSN: 2582-6018

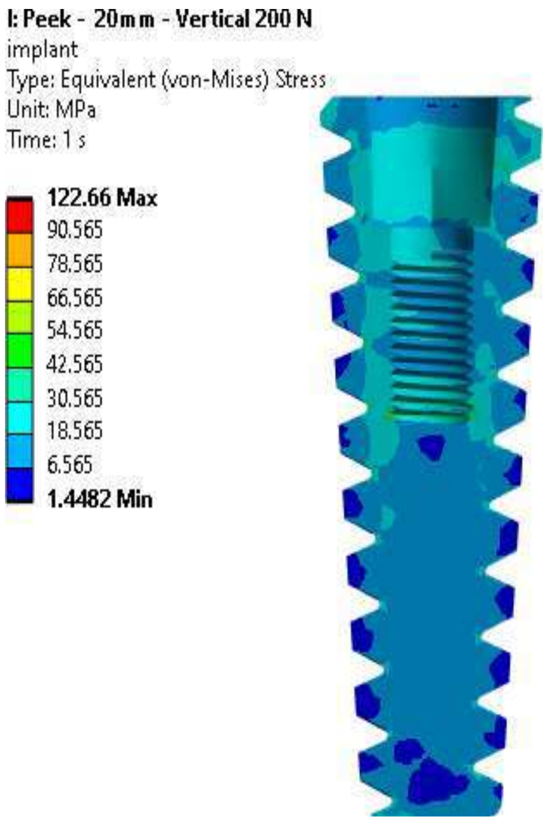


Figure 5F showing stresses in implant

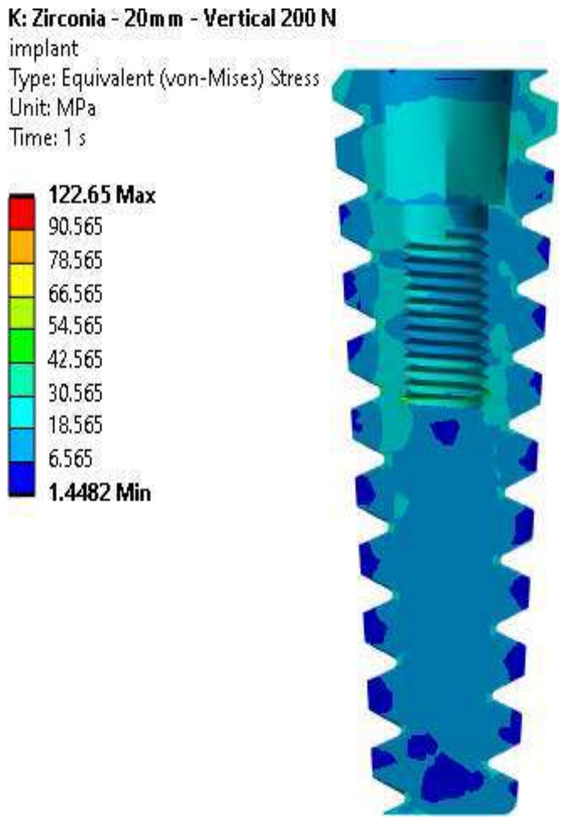


Figure 6F showing stresses in implant

PEEK(2:1)

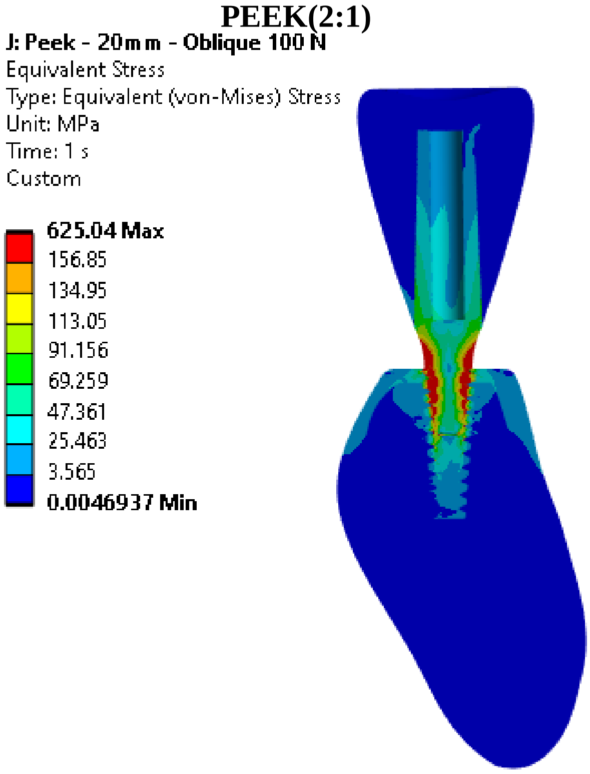


Figure 5G showing stresses overall

ZIRCONIA(2:1)

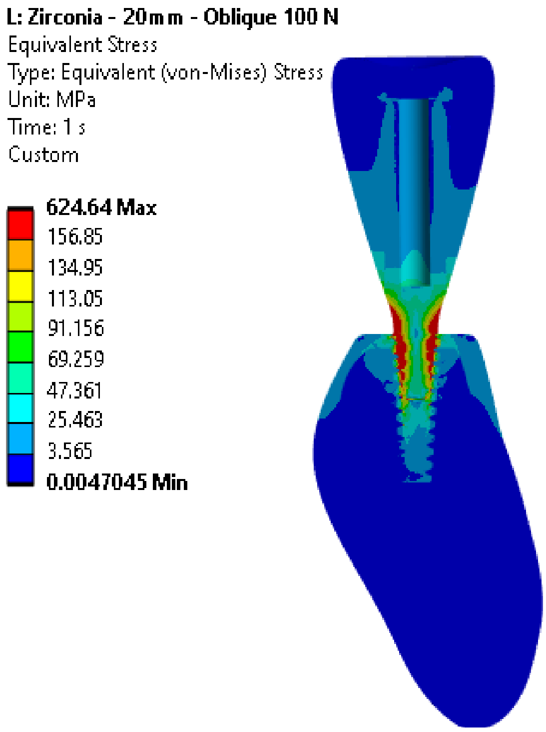


Figure 6G showing stresses overall

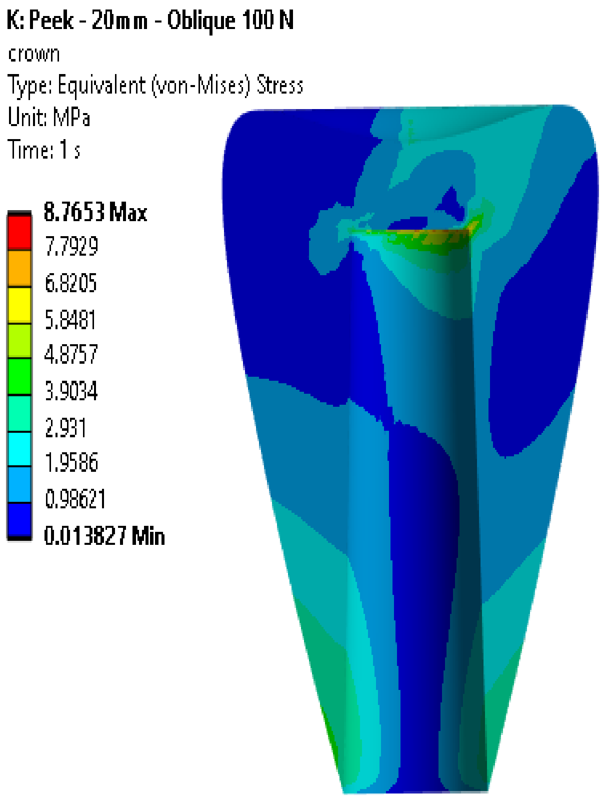


Figure 5H showing stresses in crown

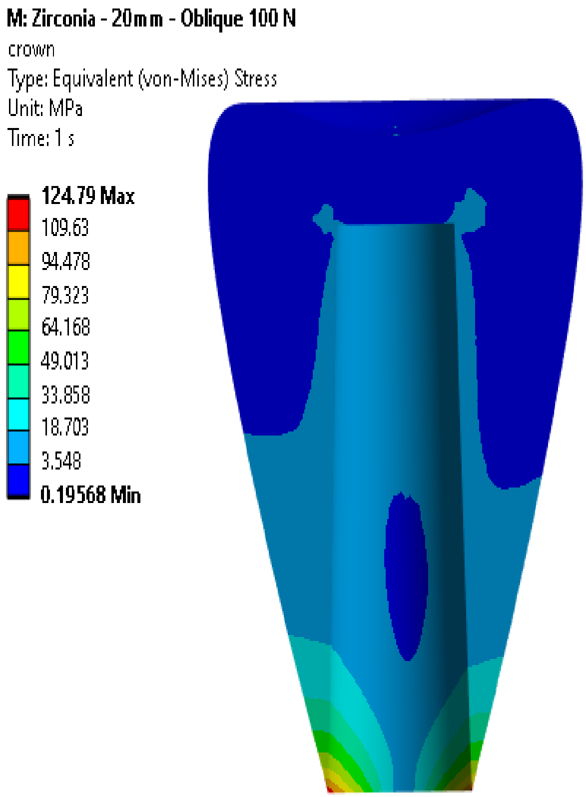


Figure 6H showing stresses in crown

PEEK(2:1)

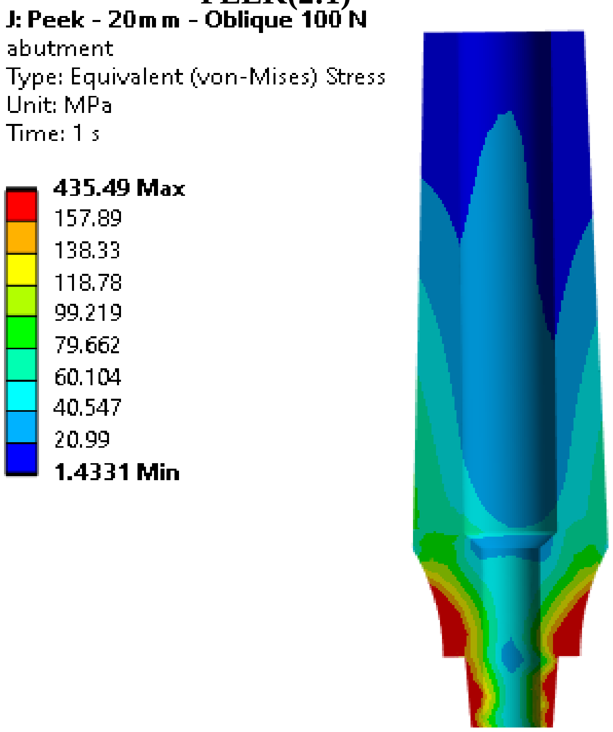


Figure 5I showing stresses in abutment

ZIRCONIA(2:1)

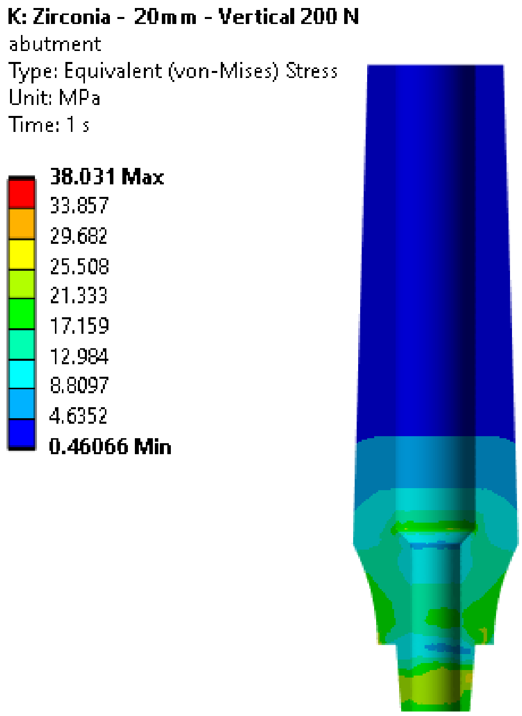


Figure 6I showing stresses in abutment

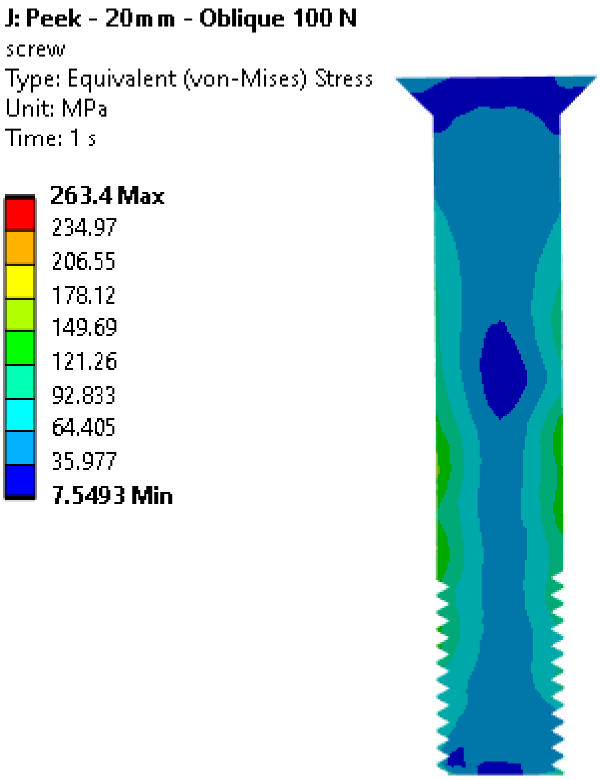


Figure 5J showing stresses in abutment screw

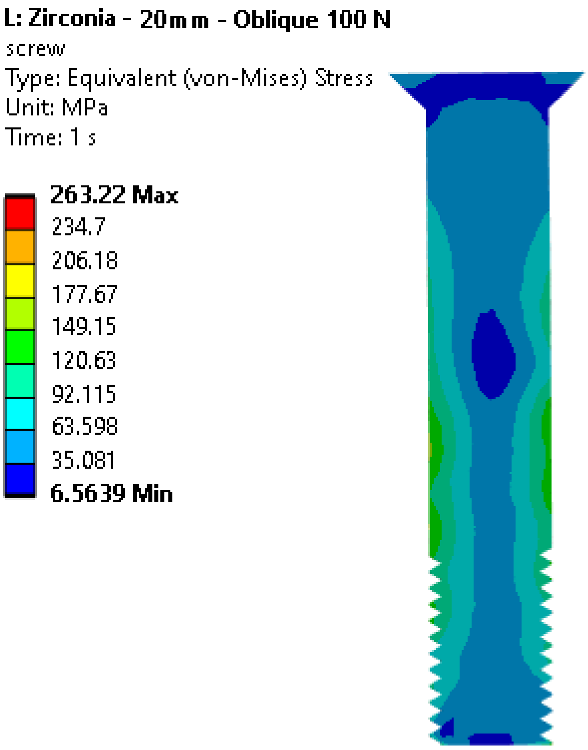


Figure 6J showing stresses in abutment screw

PEEK(2:1)

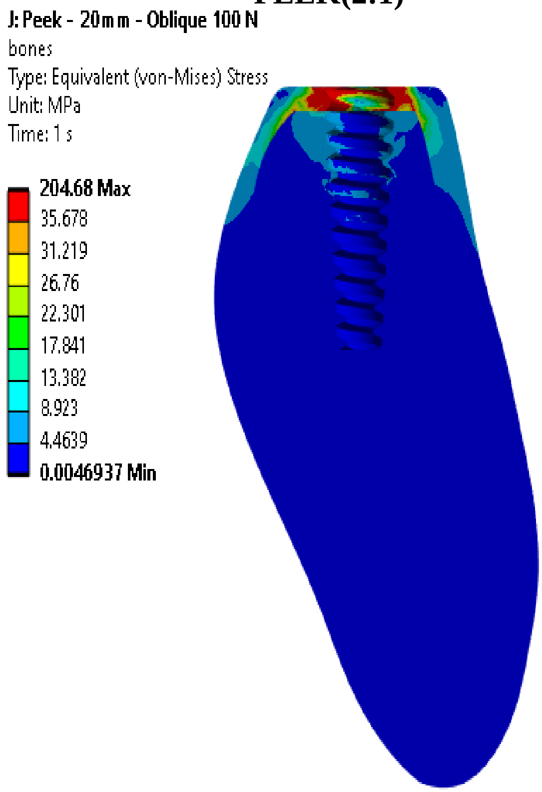


Figure 5K showing stresses in bone

ZIRCONIA(2:1)

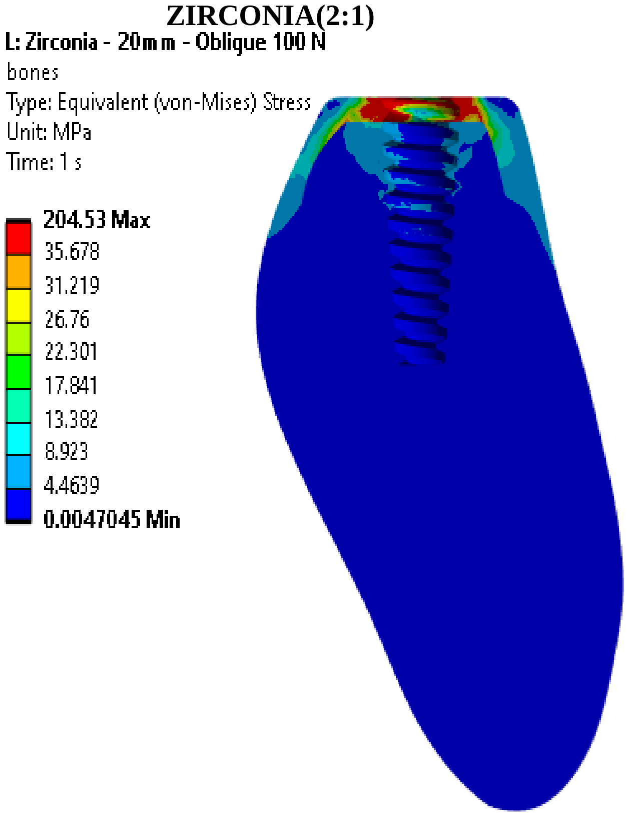


Figure 6K showing stresses in bone

International Journal Dental and Medical Sciences Research
Volume 7, Issue 5, Sept – Oct 2025 pp 132-159 www.ijdmsrjournal.com ISSN: 2582-6018

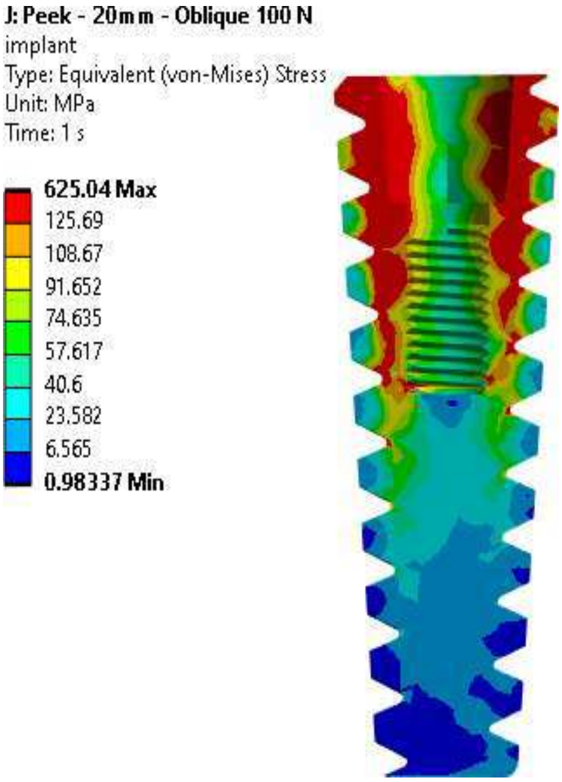


Figure 5L showing stresses in implant

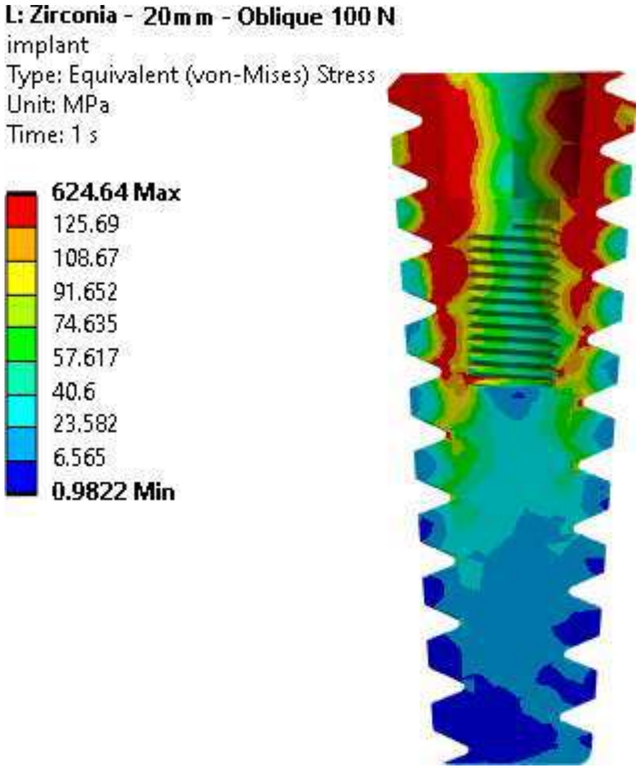


Figure 6L showing stresses in implant

IV. DISCUSSION

Dental implants have revolutionized oral rehabilitation, especially in cases of partial or complete tooth loss. As implant treatment has evolved, understanding the biomechanical factors affecting long-term success has become increasingly important. One critical parameter is the crown-to-implant (C/I) ratio, especially in cases involving vertical bone loss or limited implant length. This study aimed to evaluate how varying C/I ratios and crown materials influence stress distribution in implant systems under functional loading using finite element analysis (FEA).

Crown-to-Implant Ratio and Biomechanical Response

Our results showed a clear trend: increasing the C/I ratio resulted in a significant rise in von Mises stress values, especially around the implant collar, crestal bone, and abutment interface. This observation aligns with the basic biomechanical principle that a taller prosthesis acts like a cantilever, generating greater bending moments when lateral forces are applied.

At a 2:1 ratio, both bone and implant components experienced stress levels approaching or exceeding material yield points, particularly under oblique loading. This is clinically relevant, as higher stress may contribute to biological complications such as marginal bone loss or mechanical issues like screw loosening. These findings support the work of authors such as Tada and Ramos Verri, who reported that increasing the crown height space correlates with increased torque on implant components.

However, not all previous research agrees. Some authors have argued that short implants with higher C/I ratios can still perform successfully if osseointegration and loading conditions are favorable. Our findings suggest that while implant failure may not be immediate, elevated stresses in high C/I conditions pose long-term risks to prosthetic stability and peri-implant health.

Bone Stress Patterns

Stress distribution was most prominent in the cortical bone at the crest, particularly under oblique loading. As the C/I ratio increased from 1:1 to 2:1, stress in this region multiplied, confirming the crestal bone's role as the primary load-bearing structure. In contrast, cancellous bone showed minimal changes in stress, reaffirming its limited role in supporting direct loads.

Notably, the stress values observed in the cortical bone at higher C/I ratios during oblique loading approached or surpassed the elastic limit of human bone. This suggests a potential for microfractures or marginal bone resorption, particularly in compromised bone quality. While some studies have reported no direct link between increased C/I ratio and bone loss, the results of our simulation point to a strong correlation under lateral forces.

Implant and Abutment Response

The implant neck and first threads were consistent stress concentration points, especially under oblique load and with longer crown heights. In the 2:1 group, implant stress reached levels close to the titanium yield strength, indicating a risk of mechanical failure under extreme or repetitive load conditions.

The abutment, especially at the implant-abutment junction, also showed significant stress elevation with increasing prosthetic height. This was most pronounced under angled loads, where stress values were up to 15 times higher than those under vertical force. These findings highlight the importance of the implant-abutment connection design and the need for cautious prosthetic planning in high C/I scenarios.

Abutment Screw Performance

The abutment screw experienced a steady increase in stress as the C/I ratio rose. Under vertical load, the screw showed stable values, but oblique loading led to substantial increases—up to five times higher in some cases. While the screw did not emerge as the most vulnerable component, its location within the implant system means any failure could compromise the entire prosthetic assembly. Clinical implications include the risk of screw loosening or fracture, especially in taller restorations exposed to lateral forces.

Crown Material Comparison

A key aim of this study was to compare two commonly used restorative materials—zirconia and PEEK—in their ability to manage stress across different C/I ratios. Zirconia, known for its rigidity, consistently demonstrated higher stress values within the crown itself but did not show significant differences in stress transfer to the bone or implant compared to PEEK.

PEEK, a polymer with an elastic modulus closer to that of bone, showed lower internal stress but surprisingly offered no major advantage in reducing the stress transferred to supporting structures. While it was initially hypothesized that PEEK might act as a shock absorber, the results suggest that material choice alone cannot offset the biomechanical challenges posed by increased C/I ratios.

Clinical Implications

This study underscores the critical importance of managing the crown-to-implant ratio during implant planning. Whenever possible, clinicians should aim to:

- Minimize prosthetic height to reduce mechanical strain.
- Limit oblique loading through careful occlusal adjustment to ensure forces are directed more vertically.
- Consider crown material selection, although it appears secondary to the influence of prosthetic height.

Although PEEK may offer some biomechanical benefits due to its flexibility, it does not drastically alter stress patterns in the bone or implant compared to zirconia. Therefore, in high-risk cases involving tall prostheses, relying solely on restorative material properties is insufficient to prevent complications.

V. LIMITATION

While this study offers meaningful insights into the mechanical behavior of implant-supported restorations with varying crown-to-implant ratios, certain constraints should be noted.

First, the simulations were performed under idealized conditions, assuming perfect integration between bone and implant, and using simplified material behavior models. Biological tissues were treated as uniform and elastic, which does not entirely represent their complex, real-life characteristics.

Second, only static forces were applied in vertical and oblique directions. In clinical situations, forces acting on implants are dynamic and vary with time, position, and function. The absence of cyclic or fatigue loading limits the understanding of long-term performance.

Additionally, the study did not simulate the remodeling capacity of bone over time or account for patient-specific differences in bone quality or density. While the models were derived from CBCT scans, detailed anatomical variations such as trabecular patterns and cortical irregularities were simplified.

Moreover, soft tissues and the periodontal ligament were excluded, although they influence load absorption and force transmission, particularly in natural teeth.

Lastly, the analysis focused on a single implant in one location. Variations in arch position, multiple implant configurations, or other prosthetic designs might yield different results.

International Journal Dental and Medical Sciences Research
Volume 7, Issue 5, Sept – Oct 2025 pp 132-159 www.ijdmsrjournal.com ISSN: 2582-6018

VI. CONCLUSION

This finite element analysis revealed that increasing the crown-to-implant ratio results in elevated stress across implant components, especially under angled loading. The implant neck, abutment, and crestal bone were particularly affected as the crown height increased.

Though zirconia crowns showed higher stress within the crown structure, both zirconia and PEEK transferred comparable levels of stress to the supporting structures.

These findings reinforce the importance of maintaining a balanced prosthetic design, reducing lateral loading, and selecting suitable implant dimensions to ensure mechanical stability and enhance long-term clinical outcomes.

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