

A Three-dimensional Finite Element Analysis of Stress Distribution in the Cortical Bone in Single Tooth Implant and Post Core-treated Tooth subjected to variable Loads

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ABSTRACT

Purpose: In spite of many advances in the field of prosthetic dentistry, the choice of whether to treat and retain a grossly compromised tooth or to extract and replace with an implant is debatable. Alveolar bone preservation is one of the main criteria to select the treatment option. This is directly affected by the stress generated in the cortical bone under variable loads and is therefore, relevant.

Materials and methods: Two three-dimensional finite element models were generated in relation to maxillary second premolar using ANSYS software. Model-I was parallel-tapered titanium implant with screw-retained titanium abutment and porcelain fused to metal (PFM) crown. Model-P was fiber post and composite resin core with PFM crown. Luting cement was resin cement. Both the models were surrounded by homogeneous and isotropic cortical and cancellous bone, and were subjected to variable loads of 300, 400, and 500 N in axial (0°) and nonaxial (15°, 45°) directions.

Results: Stress in the cortical bone in megapascal (MPa) in Model-I/Model-P when subjected to variable loads in newtons (N) in axial direction was 300 N – 37.6 MPa/47.3 MPa; 400 N – 50.2 MPa/63.0 MPa; 500 N – 62.7 MPa/63.0 MPa. 15° – 300 N – 68.5 MPa/65.9 MPa; 400 N – 91.3 MPa/87.9 MPa; 500 N – 114.2 MPa/87.9 MPa. 45° – 300 N – 136.3 MPa/88.9 MPa; 400 N – 181.8 MPa/118.5 MPa; 500 N – 227.2 MPa/118.5 MPa.

Conclusion: Within the limitation of this study, it was concluded that on axial loading, both the treatment modalities showed no significant difference, but on nonaxial loading, the cortical bone in the implant model showed to have considerably higher stress than post core-treated tooth model. Hence, given a choice, this study favors retaining and restoring a compromised tooth with post core and crown rather than extracting and replacing with an implant.

Keywords: Axial load, Cortical bone, Implant, Nonaxial load, Post core, Prosthodontics.

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INTRODUCTION

Severely compromised but salvageable teeth are a common clinical presentation and need to be treated after thorough assessment of various factors affecting the long-term prognosis. The two highly predictable procedures considered for the same are implant therapy and endodontic treatment. Endodontic treatment and successive post core and final restoration had been the treatment of choice for decades. However, the changing trends in implant dentistry have brought a paradigm shift from treating and preserving a severely compromised tooth by endodontics to extracting it and replacing it with an implant.¹ Preservation of surrounding structures especially the bone and predictability of the treatment are essential in selecting the treatment option.

Undoubtedly, alveolar/cortical bone plays a key role in providing support to the teeth as well as implants, which are anchored to the bone by desmodontal fibers and osseointegration respectively. Therefore, the treatment rendered should be planned with the ultimate goal to preserve the bone and surrounding structures.² Alveolar bone resorption can occur due to a variety of factors, such as endodontic pathology, periodontitis, trauma, aggressive surgical procedures during implant therapy, or surgical management of periapical infection.^{3,4} Periapical infections have been proven to be the root cause of alveolar bone resorption especially in case of maxillary teeth where buccal/labial plate is thin and porous. This results in the spread of the infection more palatally, resulting in considerable loss of alveolar height. This resultant bone loss may later require an additional augmentation procedure. Hence, preservation of alveolar bone by treating and preventing the recurrent periapical infection will spare additional augmentation procedure.⁵ Stress, regardless of its cause, always produces an alarming reaction, which increases the rate of bone resorption.⁶ Reduction or distribution of mechanical stress, i.e., applied on the alveolar bone could drastically improve the blood flow and hence, favor preservation.

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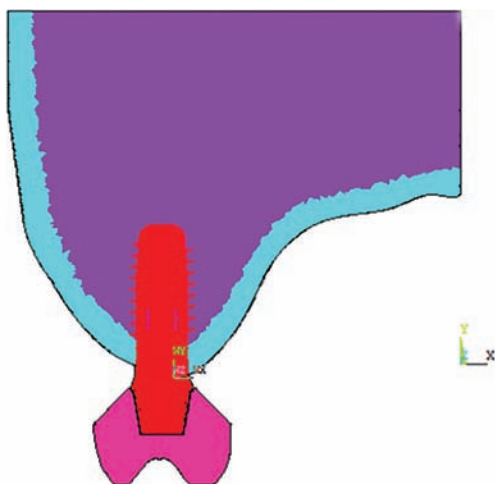


Fig. 1: Single tooth implant model (Model-I)

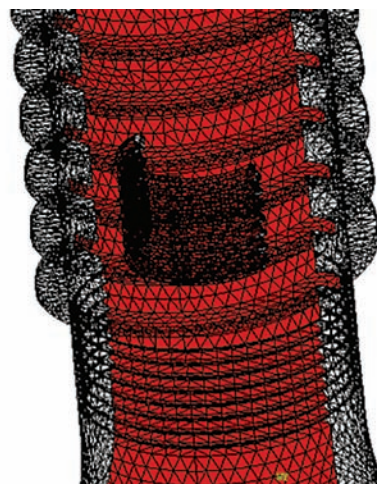


Fig. 2: Meshing of single tooth implant model (Model-I)

Implant prognosis is greatly influenced by the amount and direction of load applied.⁷ Excessive masticatory load due to improper treatment planning can result in early crestal bone loss as well as early implant failure, which are not uncommon. Also, consequences of excessive masticatory load may lead to failure in endodontically⁸ and post core-treated tooth, which in turn results in bone resorption especially on buccal plate or ankylosis due to periodontal ligament resorption.⁵

Numerous factors have been shown to contribute to the predictability of both implant and endodontically treated teeth, but success in implant is different than success for endodontics.⁹ Success of implant depends on quality and quantity of bone, masticatory load, and type of restoration and implant design, whereas the factors that have been linked to success of endodontically treated and restored tooth relies on periodontal condition and quality of the restoration.^{10,11} There are also fundamental differences in the oral environments of patients receiving either implant or endodontics therapy. Implants tend to be placed in the context of good oral health, whereas endodontic treatment usually is performed in the presence of active disease.⁹

Due to insufficient information on the comparison of these two treatment modalities, the selection of one over the other is more of operator choice and skill and hence, more subjective. As stress plays a major role in the resorption of bone and directly or indirectly influences the prognosis of both the treatment modalities, it has been considered for this study.

MATERIALS AND METHODS

For the purpose of this study, two computer-generated isotropic and homogeneous finite element analysis models were constructed:

Model-I (implant): Single tooth implant restored with crown, surrounded by anatomic structures.

Model-P (post core): Endodontically treated tooth, restored with post core and crown, surrounded by anatomic structures.

Graphic preprocessing software – ANSYS version 10 – was used for creating the geometric representation of Model-I and Model-P with surrounding anatomic structures. These models were of established dimensions possessing the physical properties, such as Young's modulus and Poisson's ratio, of normal anatomic structures and materials utilized to study the stress distribution pattern.

MODEL-I

Model-I represented an osseointegrated single-tooth implant with a crown, surrounded by isotropic and homogeneous cortical and cancellous bone as seen in Figures 1 and 2. The Young's modulus values used to generate Model-I are tabulated in Table 1. The parameters used to generate Model-I are as follows:

- Residual alveolar bone width: 4 mm.¹²
- Bone quality: D-11¹³
- Cortical bone thickness: 2 mm¹⁴
- Implant – parallel-tapered Ti alloy (Ti, 6Al, 4V) implant¹⁵
- Abutment – titanium alloy (Ti, 6Al, 4V)
- Connecting screw – titanium alloy (Ti, 6Al, 4V)

Table 1: Young's modulus and Poisson's ratio for Model-I

Material	Young's modulus (e)	Poisson's ratio (v)	References
Cortical bone	13.7	0.30	[17]
Cancellous bone	1.4	0.30	[17]
Implant body, abutment and screw (Ti, 6Al, 4V alloy)	110	0.35	[17]
Co-Cr metal	218	0.33	[17]
Porcelain	82.8	0.35	[17]
Resin cement	8.0	0.3	[16]

- Crown – PFM (Vita metal ceramics and Bellabond Ni-Cr alloy coping)
- Luting agent for crown – Panavia F Resin cement¹⁶

MODEL-P

Model-P represented a grossly decayed single-rooted maxillary second premolar with 2 mm of coronal tooth structure remaining postendodontically, restored with post core and porcelain fused to metal (PFM) restoration as seen in Figures 3 and 4. The Young’s modulus and Poisson’s ratio used for modeling are tabulated in Table 2 and following details were used to generate this model:

- Remaining tooth structure:
 - Coronal tooth structure: Class V with no remaining cavity wall with 2 mm of ferrule all around¹⁸
 - Root length: 14 mm¹⁹
 - Total length: 16 mm (root length + remaining tooth structures)
 - Surrounding structure:
 - Cementum: 0.12 mm²⁰
 - Periodontal membrane: 0.2 mm²⁰
 - Bone quality: D-1¹³
 - Cortical bone thickness: 2 mm¹⁴
- Post and core specification:
 - Remaining gutta percha after post space preparation: 4 mm²¹
 - Post space preparation width: 1.1 mm²¹
 - Post used: Parallel-tapering fiber post²¹
 - Post diameter²¹
 - Apical – 1 mm
 - Coronal – 1.8 mm
 - Luting agent for post – Panavia F resin cement¹⁶
 - Core – Dual-cure titanium-reinforced composite resin (Ti-core)
- Crown – PFM crown (Vita metal ceramics and Bellabond Ni-Cr alloy coping)

Table 2: Young's and Poisson's ratio for Model-P

Material	Young's modulus (e)	Poisson's ratio (v)	Reference
Cortical bone	13.7	0.30	[17]
Cancellous bone	1.37	0.30	[17]
Cementum	18.6	0.31	[23]
Periodontal ligament	0.0689	0.45	[24]
Dentin	18.6	0.31	[24]
Mucosa	10	0.40	[23]
Fiber post	15.0	0.28	[24]
Resin cement	8.0	0.30	[16]
Porcelain	82.8	0.35	[17]
Co-Cr metal	218	0.33	[17]

- Thickness of metal coping was 0.5 mm and porcelain thickness used was 1.3 mm.²²
- Luting agent for crown – Panavia F Resin cement¹⁶

Each finite element model was divided into small elements. Each element was interconnected at a number of discrete points called nodes. Each model was meshed by elements defined by 4 to 12 nodes. The displacement of each of these nodes was calculated to determine the maximum Von Mises stress throughout the structure. The types of elements and nodes used for this study were tetrahedron and four-noded shell elements in configuration. Number of elements and nodes used in Model-I was 940,994 and 184,490 respectively, and for Model-P it was 549,298 and 107,349 respectively. The result depicted maximum stress concentration in red and minimum stress in blue. Each of these models was subjected to varying loading conditions in axial and nonaxial directions.

Force and direction in which force is applied:

- 0° – 300 N, 400 N, 500 N
- 15° – 300 N, 400 N, 500 N
- 45° – 300 N, 400 N, 500 N

The load was applied at a point where functional cusp comes in contact with each other. For maxillary premolar two-point contact was considered, one on mesial marginal

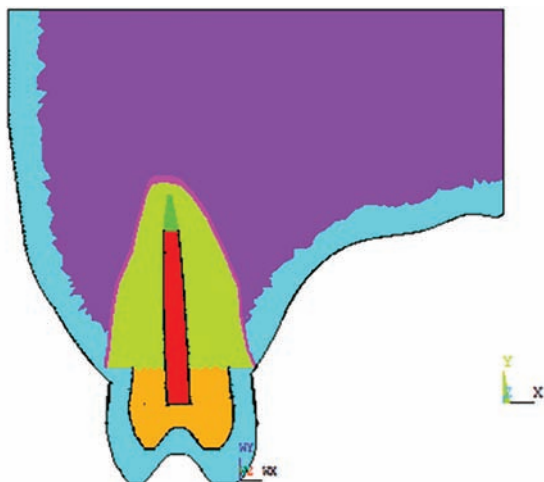


Fig. 3: Post core-treated model (Model-P)

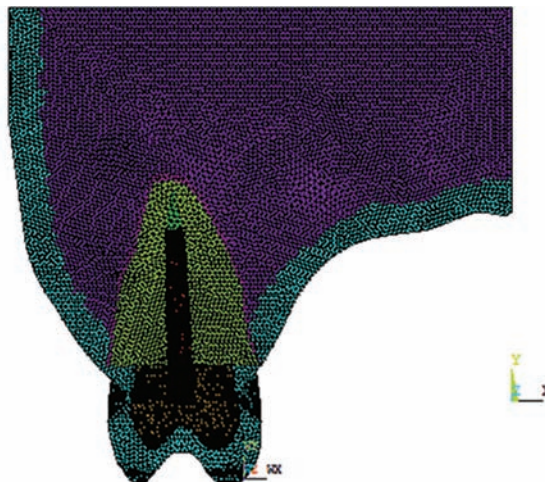


Fig. 4: Meshing of post core-treated model (Model-P)

ridge and one on the palatal cusp tip.²⁵ For nonaxial loading – load was applied at 15 and 45° from the bottom of the crown. Maximum Von Mises (Σ_v) stress equivalent was observed and compared.

RESULTS

Here, maximum Σ_v (Von Mises) stress produced in cortical bone of Model-I and Model-P under varying loads of 200, 300, 400, and 500 N in axial (0°) and nonaxial (15°, 45°) direction was observed and has been tabulated in Table 3 and the same has been represented in Graph 1.

On 300 N Loading in Axial and Nonaxial Directions

At 0°, maximum Σ_v stress produced in Model-I was negligibly lesser than that produced in Model-P as seen in Figures 5 and 6.

At 15°, maximum Σ_v stress produced in Model-I was negligibly higher than that of Model-P as seen in Figures 7 and 8.

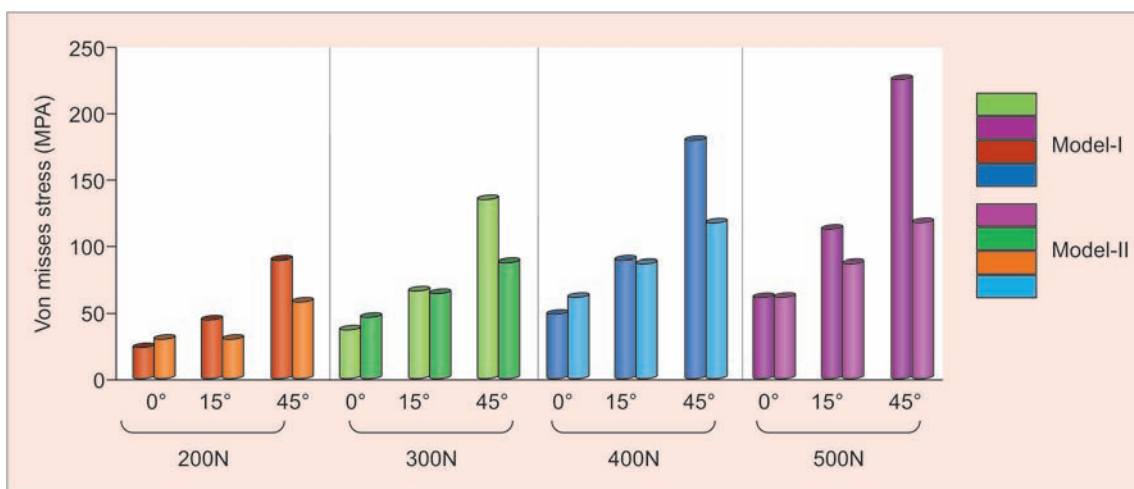
Table 3: Maximum Von Mises stress produced in cortical bone

Load	Direction	Model-I	Model-P
300 N	0°	37.6564	47.313
	15°	68.5319	65.9917
	45°	136.356	88.9465
400 N	0°	50.2086	63.0839
	15°	91.3759	87.989
	45°	181.808	118.595
500 N	0°	62.7607	63.0839
	15°	114.22	87.989
	45°	227.26	118.595

At 45°, maximum Σ_v stress produced on Model-I was approximately two times higher than that produced in Model-P as seen in Figures 9 and 10.

On 400 N Loading in Axial and Nonaxial Directions

At 0°, maximum Σ_v stress produced in Model-I was negligibly lesser than that of Model-P as seen in Figures 11 and 12.



Graph 1: Stress produced in cortical bone of Model-I and Model-P

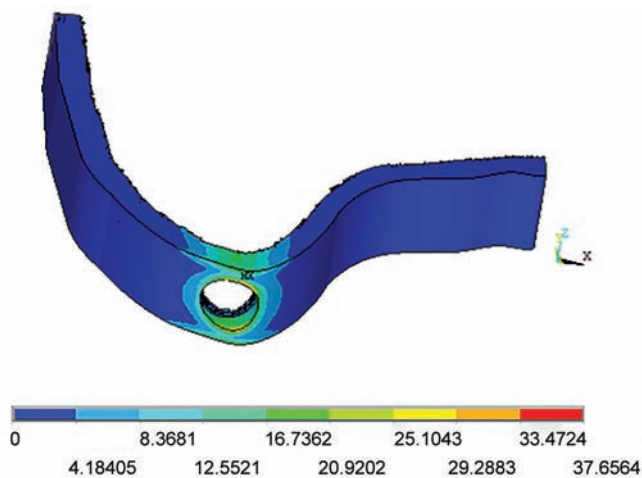


Fig. 5: Stress produced in cortical bone of Model-I at 300 N force at 0° (37.6 MPa)

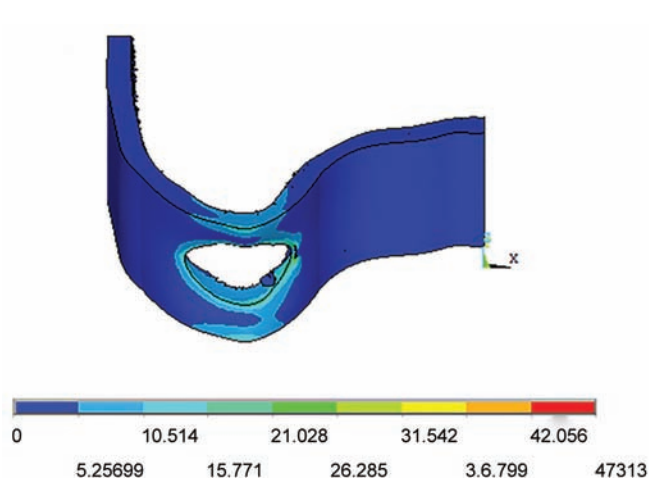


Fig. 6: Stress produced in cortical bone of Model-P at 300 N force at 0° (47.3 MPa)

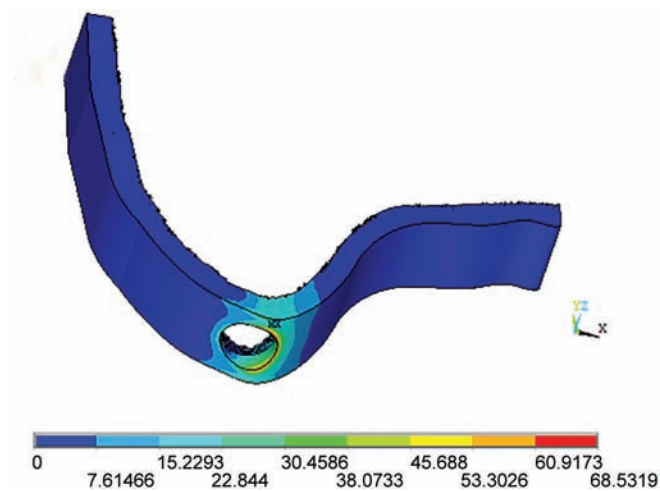


Fig. 7: Stress produced in cortical bone of Model-I at 300 N force at 15° (68.5 MPa)

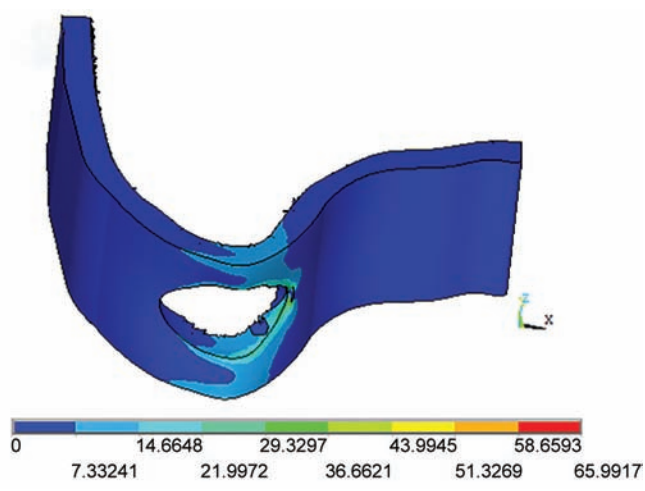


Fig. 8: Stress produced in cortical bone of Model-P at 300 N force at 15° (65.9 MPa)

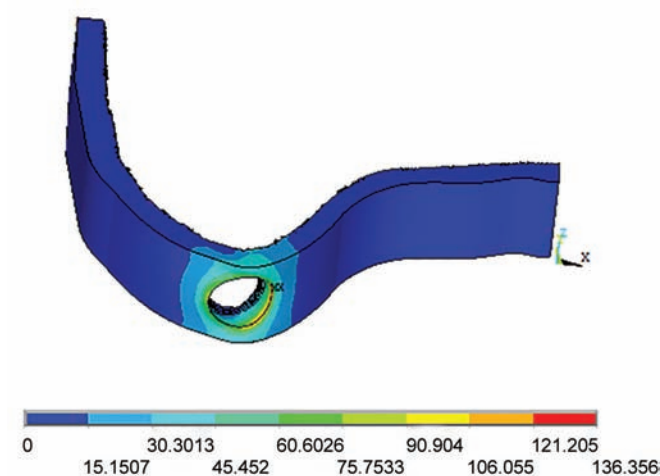


Fig. 9: Stress produced in cortical bone of Model-I at 300 N force at 45° (136.3 MPa)

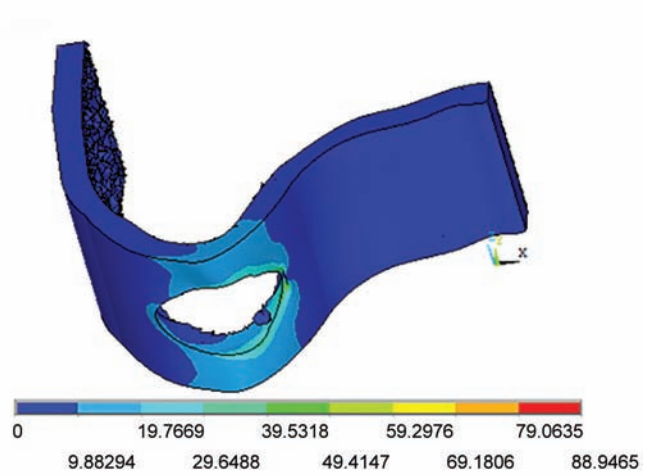


Fig. 10: Stress produced in cortical bone of Model-P at 300 N force at 45° (88.9 MPa)

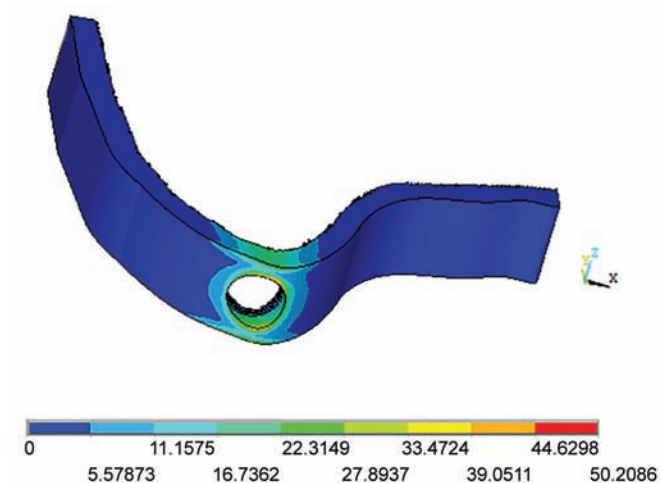


Fig. 11: Stress produced in cortical bone of Model-I at 400 N force at 0° (50.2 MPa)

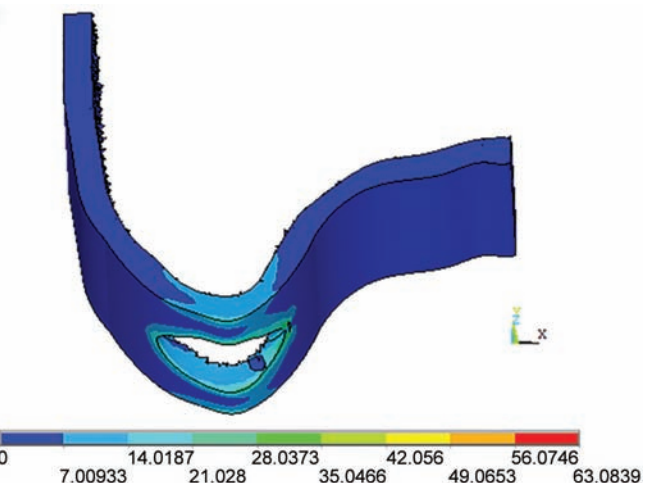


Fig. 12: Stress produced in cortical bone of Model-P at 400 N force at 0° (63.08 MPa)

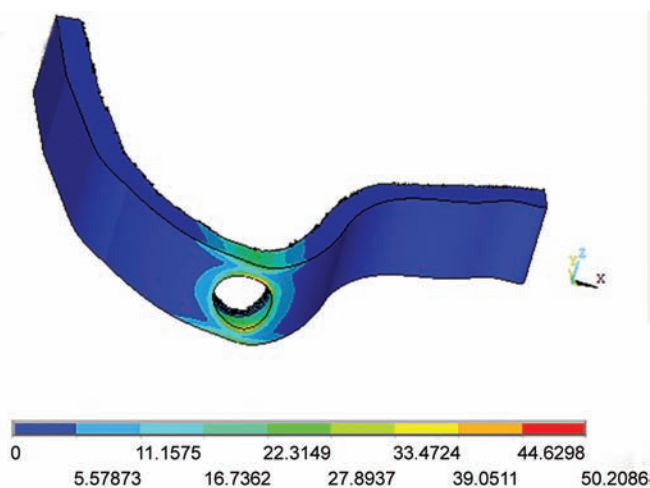


Fig. 13: Stress produced in cortical bone of Model-I at 400 N force at 15° (91.3 MPa)

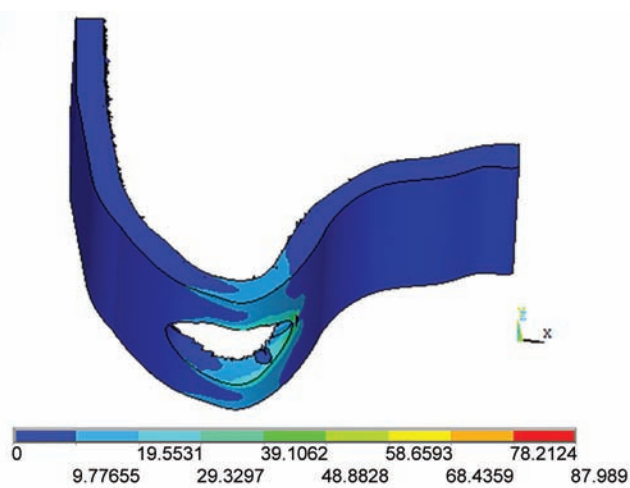


Fig. 14: Stress produced in cortical bone of Model-P at 400 N force at 15° (87.9 MPa)

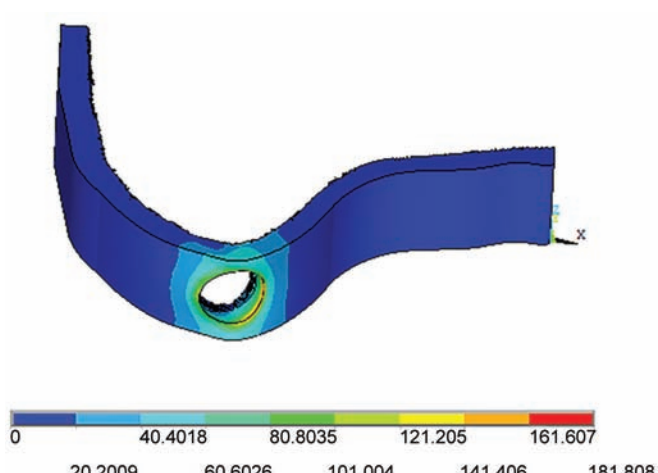


Fig. 15: Stress produced in cortical bone of Model-I at 400 N force at 45° (181.8 MPa)

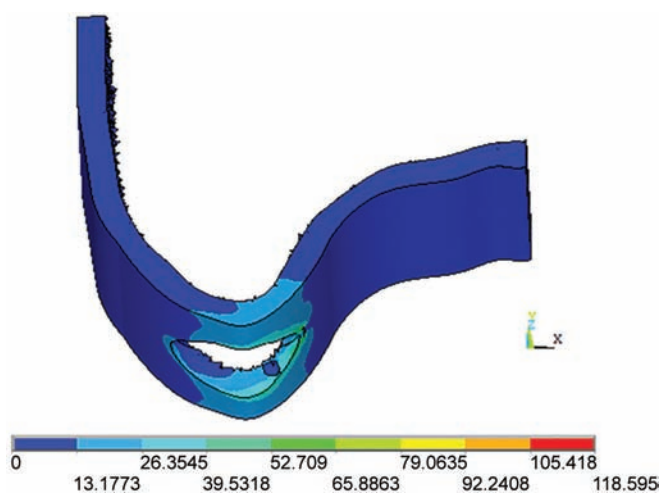


Fig. 16: Stress produced in cortical bone of Model-P at 400 N force At 45° (118.5 MPa)

At 15°, maximum Σ_v stress produced in Model-I was negligibly higher than that Model-P as seen in Figures 13 and 14.

At 45°, maximum Σ_v stress produced in Model-I was two times higher than that produced in Model-P, as seen in Figures 15 and 16.

On 500 N Loading in Axial and Nonaxial Direction

At 0°, maximum Σ_v stress produced in both the models showed no significant difference, as seen in Figures 17 and 18.

At 15°, maximum Σ_v stress produced in Model-I was two times higher than Model-P, as seen in Figures 19 and 20.

At 45°, maximum Σ_v stress produced in Model-I was approximately two times higher than Model-P, as seen in Figures 21 and 22.

On comparing maximum Σ_v stress produced in cortical bone of Model-I and Model-P on axial loading,

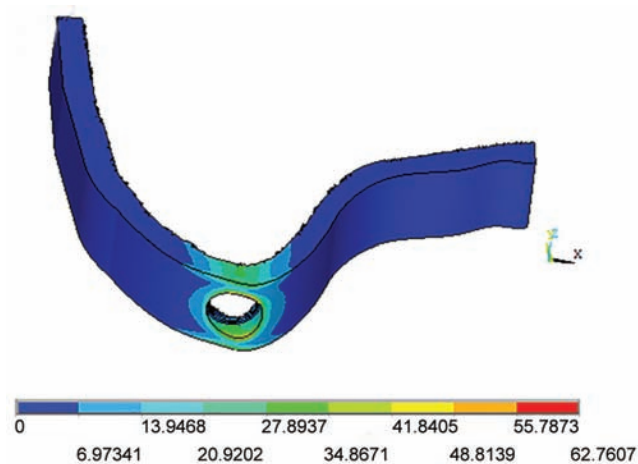


Fig. 17: Stress produced in cortical bone of Model-I at 500 N force at 0° (62.7 MPa)

it was observed that stress produced in Model-I was negligibly lesser than that produced in Model-P, which is of not much significance. On nonaxial loading of 15°, stress produced was higher in Model-I when

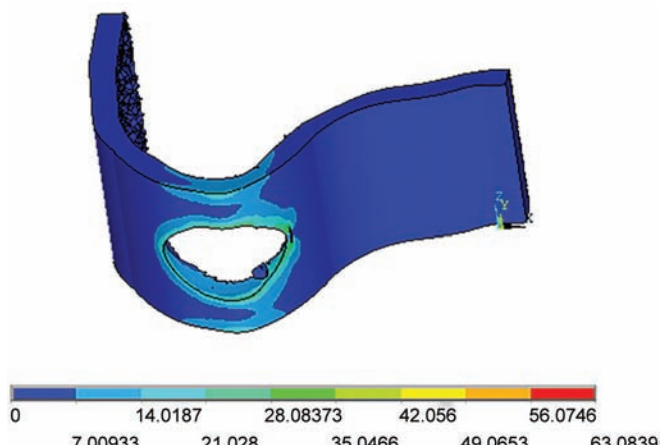


Fig. 18: Stress produced in cortical bone of Model-P at 500 N force at 0° (63.08 MPa)

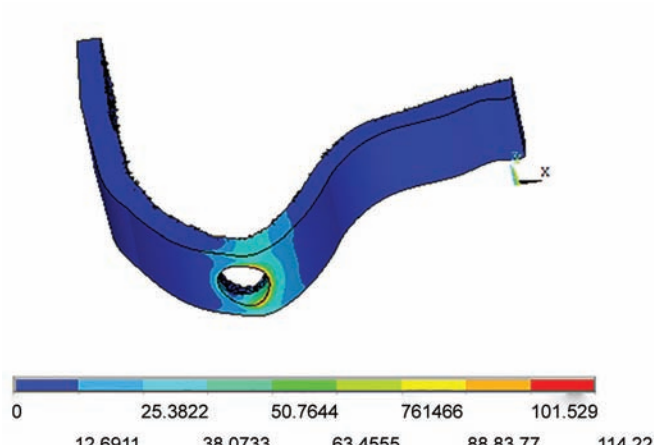


Fig. 19: Stress produced in cortical bone of Model-I at 500 N force at 15° (114.2 MPa)

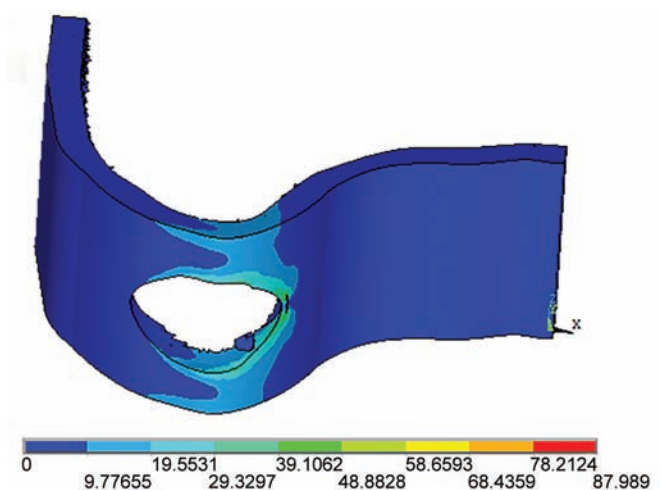


Fig. 20: Stress produced in cortical bone of Model-P at 500 N force at 15° (87.9 MPa)

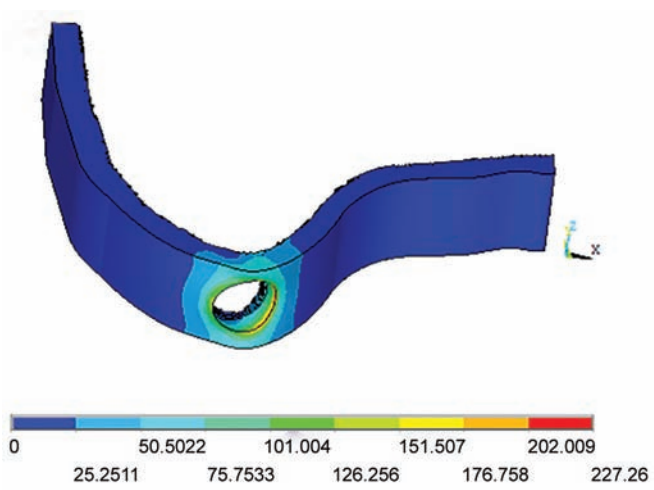


Fig. 21: Stress produced in cortical bone of Model-I at 500 N force at 45° (227.2 MPa)

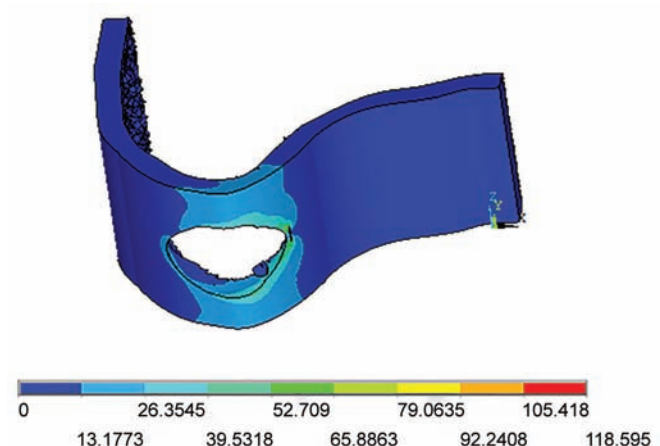


Fig. 22: Stress produced in cortical bone of Model-P at 500 N force at 45° (118.5 MPa)

compared with Model-P but not of much significance. But on nonaxial loading of 45°, stress produced was significantly higher (almost two times) in Model-I than Model-P.

DISCUSSION

Both endodontics and implant therapy were compared in this study in order to assist decision-making of whether to retain a tooth requiring endodontics and post core placement or to extract the same and replace it with implant.²⁶ Various studies have been conducted to compare both the treatment modalities, but due to insufficient data regarding success criteria among both the treatments, direct comparison becomes subjective.¹⁰ Although few studies have compared these two treatment modalities based on the success and survival rate, it had been concluded that implant-supported single crowns have a success rate, i.e., generally superior to the success rate associated with nonsurgical endodontic and post core-treated tooth.²⁷ But the survival rates for implant-supported single crowns and root canal-treated tooth are almost similar.^{9,10,27,28}

Functional occlusal loading on an implant triggers the remodeling of the surrounding alveolar bone. A mild load induces a bone remodeling response and reactive woven bone production. However, excessive loads result in



microfractures, which in turn cause osteoclastogenesis.²⁹ When the bone remodeling capacity is insufficient to keep pace with the microdamage, these defects accumulate and coalesce to form a bigger defect.²⁷ As a consequence, the defect formed will fill with fibrous tissues and microorganisms. Eventually, severe bone loss occurs, decreasing the bony support around the implant and increasing the risk of implant failure.^{30,31}

Endodontically treated tooth are more brittle due to loss of structural integrity associated with access preparation or caries. Vertical root fracture is a common complication to root canal therapy that often calls for tooth extraction. It may be initiated during the filling procedure or subsequently because of stress factors maintained by forces of mastication. The typical pattern of bone resorption facing these teeth was described as “dehiscence” and was found in the buccal plate in 90% of the cases.² Destruction of the supporting tissues, opposite to the fracture as a result of the constant release of irritants including bacterial elements to the area, precludes any treatment other than extraction. Vertical root fracture is most often seen in maxillary and mandibular premolars.⁵

Both the models were embedded in D-1 quality of bone and 2 mm of cortical bone¹⁴ as it has showed to have more homogeneous stress distribution. Sevimey et al¹³ conducted a study to investigate the effect of four different bone qualities on stress and concluded that stress concentrations in D3 and D4 bone qualities reached the highest values at the neck of the implant and were distributed locally. A more homogeneous stress distribution was seen in the entire bone for bone groups D1 and D2, and a similar stress distribution was observed.

For Model-I, parallel-tapered titanium implant (3.75 diameter and 10 mm length) was selected as it offers advantage of both parallel (more surface area and better stress distribution) and tapered (improved primary stability).¹⁵ Implant was assumed to be placed in correct axial inclination so straight screw-type titanium abutment was considered in the study. Implant design was selected based on the stress produced by that particular parameter. For the study, square threads with thread pitch were 0.8 mm and thread width was selected to be 0.4 mm.³² Also, microthreads were included in the design as it provides better implant stability and more surface area.³³

For Model-P, class V (no remaining wall with 2 mm of ferrule) was considered for the study because it is the most difficult clinical situation to restore.¹⁸ To restore this type of clinical situation, fiber post (1.8 mm), composite resin core, and PFM crown were considered. Fiber post and composite resin core were selected for the study as they have elastic modulus similar to that of dentin, and they tend to have a better biomechanical performance and homogeneous stress distribution.²¹

Cement used in both the models was resin cement as it proved better in strength and also it adheres to the substance and acts as single unit and hence, shows better stress distribution. Also, both the models were restored with PFM crown.¹⁶

It has been observed by various studies that the normal bite force ranges from 200 to 300 N, with maximum bite force reaching up to 700 N during parafunction.³² Hence, in order to evaluate stresses in normal and parafunctional situations, load considered for the purpose of study were 300, 400, and 500 N. Also, loads were observed in both axial (0°) and nonaxial (15°, 45°) directions in order to simulate oral conditions.

Preservation of alveolar bone being the ultimate goal in both the treatment modalities, stress produced in cortical bone was evaluated. It was observed that on axial loading, stress produced in cortical bone showed no significant difference. But on nonaxial loading, stress produced was more in Model-I. According to stress hypothesis³⁴ of early crestal bone loss which is based on mathematical principle, when two objects with different Young's modulus come in contact without any intervening substance, stress concentration will be expected at the area where they first come in contact. As titanium and bone have significant difference in the Young's modulus than bone and tooth, more stress is produced in implant²⁷ bone interface resulting in loss of bone. The result of the present study also indicated the same.

CONCLUSION

Within the limitation of this study, it is concluded that axial loading affects both the treatment modalities in a similar manner. However, nonaxial loading generated significantly higher stresses resulting in greater amount of cortical bone loss in the implant model than post core-treated tooth model. Hence, given a choice, this study favors retaining and restoring a compromised tooth with post core and crown rather than extracting and replacing with an implant-supported crown.

Though the study was designed to simulate the oral conditions, a supporting *in vivo* study of the same order would remove any limitations of the present study. Including various clinical scenarios like parafunctional habits, systemic disorders, etc. could be the future scope of the study.

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