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Effect of framework and veneering materials on stress distribution in maxillary complete arch implant supported fixed prosthesis – A Finite Element Analysis

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Abstract

Statement of Problem: Type and properties of framework and veneering materials used for complete arch implant supported fixed prosthesis may affect the prognosis of prosthodontic rehabilitation in the edentulous maxilla.

Purpose: To evaluate and compare the stress distribution in maxillary complete arch implant supported fixed prosthesis with cobalt chromium and titanium framework materials and composite resin and porcelain veneering materials on application of occlusal loads.

Material and Methods: Three-dimensional finite element analysis was used to investigate the effect of two framework materials cobalt chromium (CoCr) and titanium (Ti) and two veneering materials porcelain (POR) and composite resin (CompRES) on stress distribution in an implant supported maxillary fixed prosthesis. Four finite element models with different framework and veneering material combinations were obtained from an edentulous maxilla with a FP-1 prosthesis supported by seven implants. The four models were CoCr-CompRES, CoCr-POR, Ti-CompRESand Ti-POR. A 100N oblique load was applied and the von Mises stresses were obtained in the overall prosthesis, framework, veneering material, bone and the implant.

Results: Generated stress values in the overall prosthesis, implant, bone and superstructure were the highest in the Ti-CompRES group. The veneering material exhibited the highest stress values with Ti-POR group when compared with the other groups.

Conclusion: The types of framework and veneering materials have a strong influence on stress values of implant supported prostheses. However, other clinical parameters like effect of different load inclination, angulation and type of implant connections, prosthetic component design, type of bone, osseointegration, misfit and cantilever size should be considered before selecting framework and veneering materials for the complete arch fixed implant supported prostheses.

Keywords: FP-1 Prosthesis, Finite Element Analysis, Framework material, Veneering material, Cobalt Chromium, Titanium, Porcelain, Composite Resin, Von Mises stresses

Introduction

Problems associated with conventional complete dentures like continual ridge resorption, instability, changes in facial support and reduced masticatory efficacy can be eliminated with complete arch implant supported fixed or removable prostheses.[1]

Biomechanical factors like bone quantity and quality, length, diameter and shape of the implant, nature of bone/implant interface, type of load application, type and properties of framework and veneering materials affect the clinical success of implant supported prostheses.[2]

The implant supported prosthesis consists of a framework with a veneering material. Framework materials influence the biomechanics and propagation of functional stresses to the bone–implant interface, implant, prosthetic structures and support components.[3] Framework materials have evolved from gold alloys, base metal alloys, titanium alloys, polyetheretherketone (PEEK) material to zirconia. Bergendel et al stated that carbon or graphite fibre-reinforced poly-methyl methacrylate framework material sex habited high precision and aesthetic results at a reasonable cost.[40]Titanium and zirconia are both highly biocompatible as they prevent galvanic corrosion.[46] However, there is limited long-term documentation for largerprostheses.[24]Cobalt chromium frameworks decrease stress around the implants closest to the load thus contributing to better stress distribution than silver palladium alloy frameworks.[20, 21, 23, 30] Previous studies related the rigidity of framework to high resistance of framework to bending and consequently mitigating mechanical overloading.[4, 25, 22, 31, 36, 37]

The choice of veneering material to replicate shape and aesthetics also plays an integral role in distribution of stresses to the framework, support components, implants and bone interface in complete arch prostheses.[2]Optimum association between veneering and framework materials promotes favourable distribution of stress in the prosthesis, otherwise fracture or separation of the materials can occur.[3, 4, 5]Previous studies concluded that frameworks covered with materials of low modulus of elasticity provided an internal dampening by increasing the duration of force but reducing the peak force.[11, 12, 17, 18, 19, 28, 34] However, Stegaroiu et al suggested that when acrylic or composite resin was used on the occlusal surface, resin fracture, aesthetic defects, occlusal screw loosening or fracture, abutment screw and implant fractures and resin wear were expected.[15] Ciftci et al revealed that more stresses were borne by metal frameworks with acrylic resin and composite resin veneering materials as compared to porcelain veneered metal frameworks.[16] Porcelainhasa higher elastic modulus than both composite resin and acrylic resin. Hence, it absorbs and distributes stresses to itself thus reducing the stress to the implant, bone and the superstructure in relation with the prosthesis.[2, 3, 4, 5, 16] However, Tiossi et al inferred that porcelain increased the concentration of load in the prosthesis transferring it to the bone leading to higher strain values.[32]

Failure prevention of the various materials used for the prostheses demands testing and stress analysis of the implants and tissues in vitro as well as in vivo.[5, 7] Finite Element Studies help in evaluating the mechanical behaviour of biomaterials and human tissues, considering the difficulty in making such an assessment in vivo.[9]

Restorations associated with the edentulous maxilla have the highest early implant failure rate as the opportunities for implant placement are limited due to fine and delicate trabecular bone and close proximity to the maxillary sinuses.[6, 10]

Many studies have been conducted on mandibular fixed implant supported prosthesis in the pursuit of possible combinations of dental materials for framework and veneering materials to overcome biomechanical deficiencies and optimize function and aesthetics. However, there is need for more research on prognosis of maxillary fixed implant supported prostheses. Rigid prosthetic materials are associated with greater resistance to deformation and better stress distribution to the implant, bone and the superstructure on application of occlusal loads which may improve the prognosis of the treatment.

The purpose of this finite element study is to evaluate and compare the stress distribution in maxillary complete arch implant supported FP-1 prosthesis with cobalt chromium and titanium framework materials and composite resin and porcelain veneering materials when occlusal loads are applied.

Materials and Methods

Fabrication of finite element model

A finite element maxillary model was fabricated based on a diagnostic cone beam computed tomography of the maxillary cast of a 55 year old edentulous male with an ovoid maxillary arch. An informed consent was taken from the patient with recommendations of ethics committee of Rajiv Gandhi University of Health Sciences, Bangalore, India.

The CBCT images of the maxilla cast were imported to Simple ware program converting 3D images into numerical models (Fig.1A, Fig.1B). Implant model was manually drawn from precise geometric measurements acquired from the manufacturer (Adin Dental Implants System Ltd.). Seven implants of 11mm length and 4mm diameter were modelled (Fig.1D) and virtually inserted into the edentulous maxilla model previously constructed (Fig 1E). Later, both the implant and bone model were superimposed simulating the implant placement into the bone. The implant placement sites were left central incisor region, canine regions bilaterally, second premolar regions bilaterally and first molar regions bilaterally.

Fabrication of superstructure (framework and veneer)

The design of the prosthesis was first manually designed and drawn according to FP-1 prosthesis specifications described by Misch et al with 12 masticatory units.[6] Using CAD software (Solid works 2012), the prosthesis was designed virtually with standardized conditions and methods specified by the software. A superstructure of 4mm height and 6mm width was further specified according to a study conducted by Ferreira et al.[2] The height of the superstructure was further divided into 1mm for framework material and 3mm for veneering material. The three-dimensional finite element model corresponding to the geometric model was generated using ANSYS 14.5 Pre-Processor.

Model replication with material specifications

The final finite element model was further replicated into four models which were labelled as CoCr-CompRES, CoCr-POR, Ti-POR and Ti-CompRES according to the opted material properties.

The corresponding elastic properties such as Young's modulus (E) and Poisson's ratio (μ) of the bone, implant, cobalt chromium alloy, titanium alloy, composite resin and porcelain as illustrated in Table 1 were determined by values stated by Misch et al[6] and Anusavice et al.[45] (Fig 1A-1E).

All models were considered isotropic, homogenous and linearly elastic. To simulate osseointegration condition in implants, the bone implant interface was assumed to be bonded so that no relative movement occurred in the bone implant surface. The interface conditions for the components (implant/ cylinder/ screw), metallic framework and veneering material were assumed to be bonded in all groups.

Application of loads

100 N load was applied obliquely (30 degrees to the long axis of the implant), and buccolingually in the anterior (left central incisor) and posterior region (left first molar). The load applied was sparsely distributed on the palatal cusps of the first molar in order to avoid false stress concentration in the area of load application.[2]

Analysis of stress patterns

The model was analysed by the Processor and displayed by Post Processor of Finite Element Software (ANSYS Workbench Software Version 14.5) using Von Mises stress analysis. Von Mises stress values were computed in MPa in overall prosthesis, framework, veneering material, bone and the implant. The results were displayed as colour coded maps of the finite element models.

Results

The results were compared amongst the groups for the parameters tested as illustrated in Table 2. Comparative results showed significant difference in stress levels for various combinations. Overall stress values (Fig. 7) were highest in the Ti-CompRES group (Fig. 2D) and lowest in CoCr-POR group (Fig. 2C). Stress in the overall prosthesis in Ti-CompRES (Fig. 2E) was 34.84 MPa which was 30% higher as compared to CoCr-POR group that recorded 26.66 MPa. Ti-POR (Fig. 2F) and CoCr-CompRES (Fig. 2A) groups recorded 27.72 MPa and 30.37 MPa respectively. The veneering material (Fig. 9) exhibited the highest stress values in Ti-POR (Fig. 3D) group when compared with other groups. CoCr-CompRES (Fig. 3A) group recorded 12.36 MPa which was lower by 49% as compared to Ti-POR group that recorded 18.41 MPa. Ti-CompRES (Fig. 3C) recorded 13.47 MPa and CoCr-POR (Fig. 3B) recorded 14.69 MPa. Framework stress (Fig. 10) was 30.37 MPa in CoCr-CompRES group (Fig.4A). This was 65% higher as compared to Ti-POR group (Fig. 4E) which was 18.36 MPa. Ti-CompRES (Fig. 4D) and CoCr-POR (Fig. 4C) recorded 20.40MPa and 26.66 MPa respectively. For implants (Fig. 11), von Mises stress was 44.63 MPa for Ti-CompRES group (Fig. 5E) which was 60% higher as compared to CoCr-POR group (Fig. 5C) that recorded 27.89 MPa. CoCr-CompRES group (Fig. 5A) recorded 34.53 MPa and Ti-POR (Fig. 5F) recorded 35.3 MPa. Bone stress (Fig. 12) was 12.27 MPa in Ti-CompRES group (Fig. 6C), 10.19 MPa in CoCr-CompRES group (Fig. 6A), 10.48 MPa in Ti-POR group (Fig. 6D) and 8.8 MPA in CoCr-POR group (Fig.6B). Thus, bone stress was 40% higher in Ti-CompRES group as compared with CoCr-POR group.

Discussion

The prognosis of complete arch implant supported fixed prosthesis is influenced by several factors like quantity and quality of bone, implant length, diameter shape, implant number and distribution, nature of bone-implant interface, load application type, presence of misfit and properties of framework and veneering materials.[2]

The results of this study suggest that use of rigid prosthetic materials for the framework and veneering material of the complete arch implant supported fixed prosthesis may improve the prognosis of prosthodontic rehabilitation in the edentulous maxilla. Overall stress recorded was 30% higher in titanium framework veneered with composite resin as compared with cobalt chromium framework veneered with porcelain. Base metal alloys like nickel-chrome and cobalt chromium have been used for dental supported prosthetic frameworks for decades in the United States. However, there are documented risks for hypersensitivity for nickel in Scandinavia.[26] Cobalt chromium has advantages like low cost, biocompatibility and corrosion resistance due to the passivating effect of chrome-based oxides. It has higher elastic modulus than titanium which makes it more resistant to deformation. Commercially Pure Titanium and Titanium Alloys exhibit excellent properties such as resistance to corrosion and biocompatibility resulting from Titanium oxide and satisfactory results related to implant framework fit.[39] However, the lower elastic modulus of titanium causes greater deformation and displacement of the framework inducing greater stress to the underlying prosthetic components, implants and the bone. Previous studies showed similar results relating the rigidity of superstructure materials to mitigating mechanical overloading.[4, 25, 22, 31, 37]

Veneering material also plays an important role in stress distribution in complete arch implant prostheses.[2]In this study, stress values noted in implants revealed up to 60% increase in the composite resin and titanium group as compared with porcelain and cobalt chromium group. Similarly, stress values in the bone exhibited up to 40% in composite resin and titanium group as compared with porcelain and cobalt chromium group. Composite resin and cobalt chromium group recorded stress values up to 65% higher in the framework material as compared with porcelain and titanium group. Difference of stress distribution values in different groups maybe because of dissimilar physical properties of the materials compared. Composite resin, with a low elasticity modulus, resulted in greater deflection, thus transmitting more stresses to the underlying structures. Acrylic resin, Composite resin and Porcelain have been used as veneering materials. Acrylic resin was recommended by Branemark et al. as a material of choice for the occlusal surface of implant supported complete arch prostheses. It was inferred that acrylic veneers on gold frameworks acted as shock absorbers.[39] Skalak et al stated that loading of an implant with rigid occlusal material such as porcelain or metal may result in high impulse loading of the implant and supporting bone. The prosthesis exhibited large forces with little deflection over a short time when large impact loads were generated. So, a short pulse with a high peak force was likely to produce fractures. Conversely, when the metallic frameworks were covered with materials of low modulus of elasticity, an internal dampening of forces was provided by increasing the duration but reducing the peak force. They recommended the use of acrylic resin teeth on a metallic framework as this arrangement developed a stiff and strong substructure with adequate shock protection on its outer surface.[11] However, Stegaroiu et al suggested that when acrylic or composite resin was used on the occlusal surface, resin fracture, aesthetic defects, occlusal screw loosening or fracture, abutment screw and implant fractures and resin wear were expected.[15]Porcelain has more favourable aesthetics but an accurate occlusal adjustment is required to avoid premature overload on the implants mainly during lateral-protrusive movements as its wear resistance is higher than resin.[11]

Stress values in the veneering material in this study were 49% higher in porcelain and titanium group as compared to composite resin and cobalt chromium group. These results corroborated with studies conducted by Sertgoz in 1997,[4]Ciftci et al in 2001,[16] Assuncao et al in 2010,[24] Teigan et al in 2012,[30] Bacchi et al in 2013,[31]Menini et al in 2013 and 2015,[34,36] Ferreira et al in 2014,[2] Grando et al in 2014,[5]and Coelho et al in 2016.[38]These studies postulated that rigid porcelain absorbed and distributed stresses to itself and transferred less stress to the infrastructure, implant and bone.

Optimum association between veneering and framework materials from mechanical and biological aspects promotes correct distribution of stress during function and subsequently improving reliability of implant supported prostheses.[5] Sertgoz in 1997, suggested cobalt chromium for framework and porcelain veneer as the optimal material combination for superstructure in complete arch implant supported fixed prosthesis as it optimizes stress distribution.[4] Tiegan et al demonstrated superior clinical performance of cobalt chromium frameworks with porcelain veneering material over gold alloy and acrylic resin veneering material. Cobalt chromium was a first choice of metal alloy for fabricating frameworks due to higher dimensional stability with high fused ceramics than any other alloy.[30] Rubo et al in 2010 and Menini et al in 2015, stated that the higher modulus of elasticity of cobalt chromium allowed even distribution of load among implants. This allows fabrication of less bulky frameworks which would be an advantage if intraoral space is limited. [20, 36]

The limitations of this study are that the connecting screws at abutment-implant and prosthesis-abutment interfaces were not modelled and all connections were designed as rigid. Previous studies have revealed that stress distribution is more significant in screws, abutments, infrastructure and implant.[3,4] Also, Finite Element Analysis studies need to be compared with parallel in vitro experimental results to validate simulated models as these studies make several assumptions and simplifications related to material properties, geometry, load, and interface conditions which affect the predictive accuracy of the models.[8,9]

Further scope of this study, would be the incorporation of parameters like effect of different load inclination, angulation and type of implant connections, prosthetic component design, type of bone, osseointegration, misfit and cantilever size. In vitro and In vivo studies should also be conducted to validate experimental results. The findings of the present study could be helpful to support the clinical decision making for the framework and veneering materials for implant supported fixed prostheses.

Conclusion

Based on the results and within the limitations of this study, it can be concluded that:

The types of framework and veneering materials have a strong influence on stress distribution values of implant supported prostheses under occlusal loading.

The combination of Composite resin veneer and Titanium framework generated maximum von Mises stresses in the overall prosthesis, bone, implant and the superstructure.

Porcelain veneer and Titanium framework combination exhibited the highest von Mises stress in the veneering material.

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Legend Tables and Figures

Material	Elastic Modulus (MPa)	Poisson's Ratio	Reference
Type II Bone	5500	0.3	6
Titanium Implant	103000	0.35	6
Composite Resin	30000	0.2	45
Porcelain	70000	0.22	45
Titanium	102000	0.33	45
Cobalt Chromium	240000	0.33	45

Table 1: Properties of Structures and Materials Used In the Models

Group Stress	Bone Stress (MPa)	Implant Stress (MPa)	Framework Deformation (MPa)	Veneer (MPa)	Overall (MPa)	Overall (MPa)
Ti-CompRes	12.27	44.628	20.40	13.47	34.84	0.0346
CoCr-CompRes	10.189	34.53	30.37	12.36	30.37	0.02862
Ti-Por	10.48	35.3	18.36	18.41	27.721	0.0288
Cocr-Por	8.8	27.89	26.66	14.69	26.66	0.024

Table 2: Comparative Stress Distribution Results

Methodology

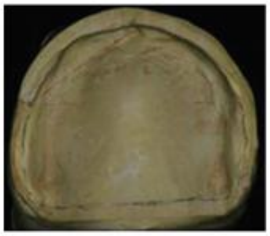

Fig. 1A Maxillary Cast of the edentulous patient with an ovoid maxillary arch

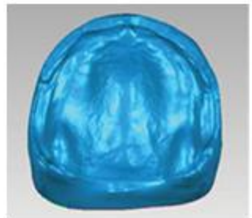

Fig. 1B 3D computerized image of representative edentulous maxillary cast

Fig. 1C Modelling of Edentulous Maxillary Cast with implant placement sites

Fig. 1D Modelling of implants

Fig. 1E Implant Placement

Fig. 1F Modelling of Veneering Material

Fig. 1G Modelling of framework with veneering material

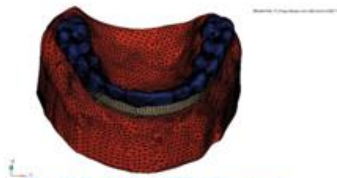

Fig. 1H Modelling of FP-1 Prosthesis with framework and veneering material

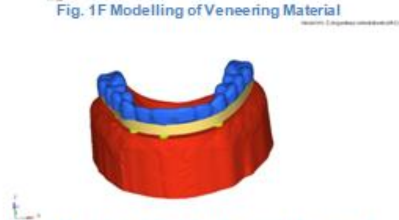

Fig. 1I Modelling of FP-1 Prosthesis with framework and veneering material

Overall Stress

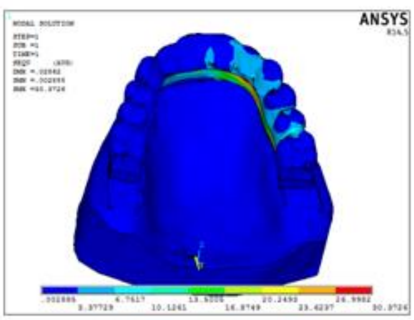

Fig. 2A Overall Stress- Cobalt Chromium framework and Composite Resin Veneer I

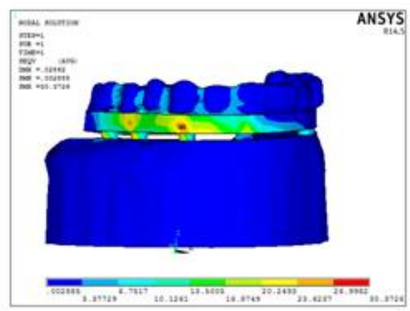

Fig. 2B Overall Stress- Cobalt Chromium framework and Composite Resin Veneer II

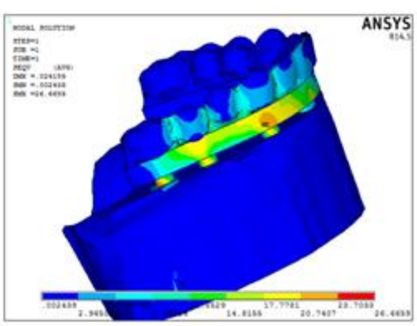

Fig. 2C Stress Concentration in Overall Prosthesis- Cobalt Chromium framework and Porcelain Veneer

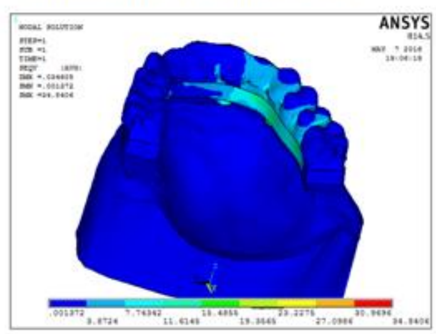

Fig. 2D Overall Stress Distribution- Titanium framework and Composite Resin Veneer

Overall Stress

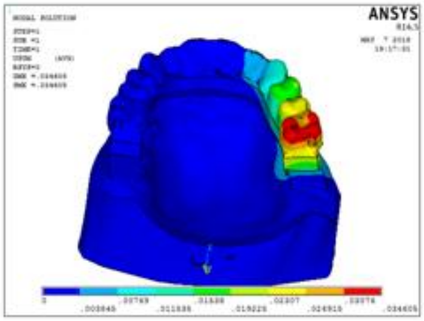

Fig. 2E Overall Prosthesis Displacement-Titanium framework and Composite Resin Veneer

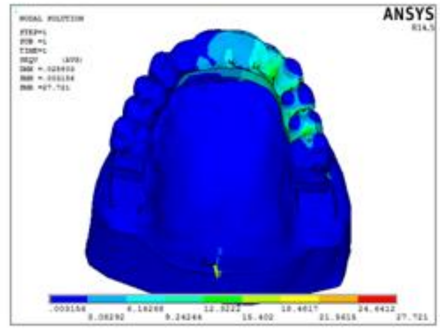

Fig. 2F Overall Stress Distribution- Titanium framework Porcelain Veneer

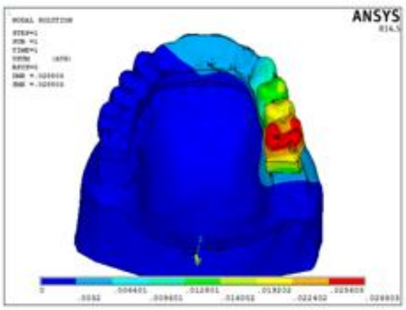

Fig. 2G Overall Prosthesis Deformation- Titanium framework and Porcelain Veneer

Veneering Material Stress

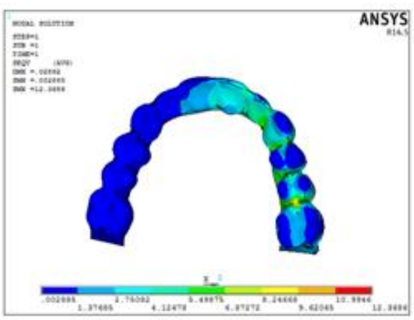

Fig. 3A Stress Distribution in Veneer-Cobalt Chromium Superstructure and Composite Resin Veneer

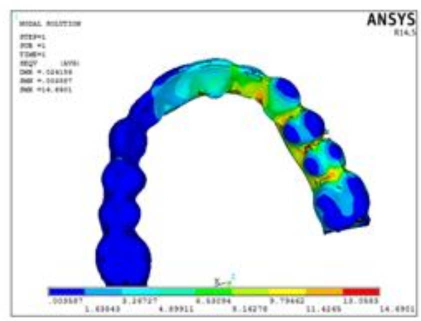

Fig. 3B Stress Distribution in Veneer - Cobalt Chromium Superstructure and Porcelain Veneer

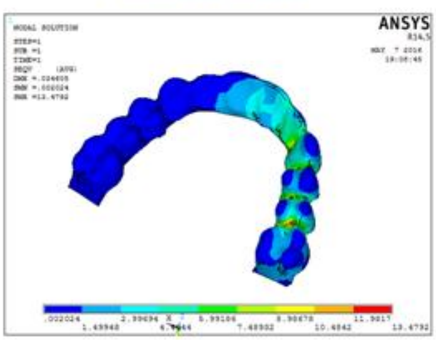

Fig. 3C Stress Distribution in Veneer- Titanium Superstructure and Composite Resin Veneer

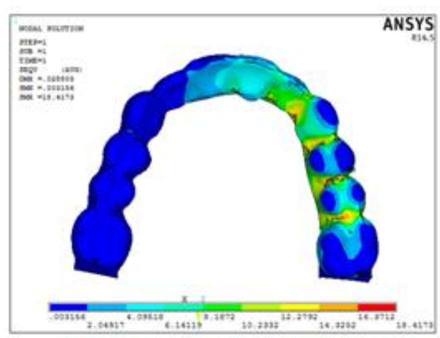

Fig. 3D Stress Distribution in Veneer- Titanium Superstructure and Porcelain Veneer

Framework Material Stress

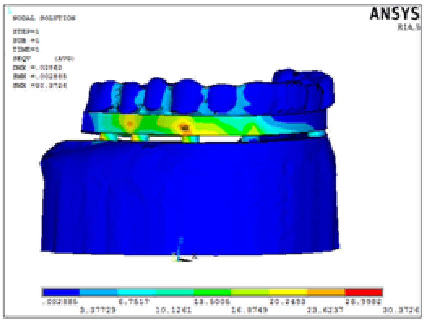

Fig. 4A Stress Distribution in Framework: Cobalt Chromium framework and Composite Resin Veneer I

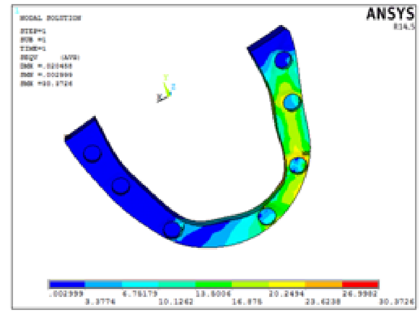

Figure 4B Stress Distribution in Framework: Cobalt Chromium Superstructure and Composite Resin Veneer II

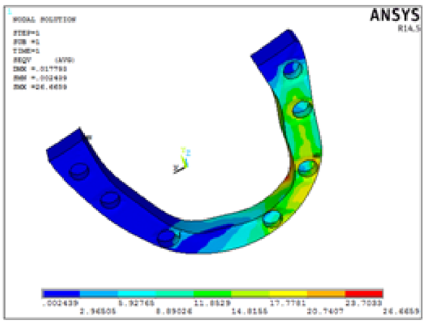

Fig. 4C Stress Distribution in Framework – Cobalt Chromium framework and Porcelain veneer

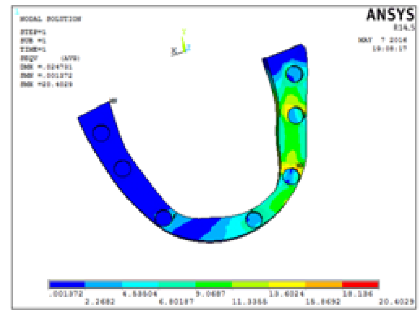

Fig. 4D Stress Distribution in Framework – Titanium framework and Composite Resin Veneer

Framework Material Stress

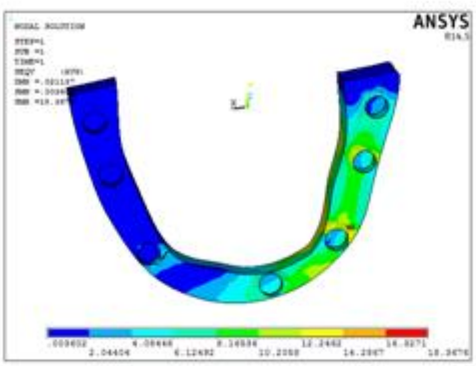

Fig. 4E Stress Distribution in framework- Titanium framework and Porcelain Veneer

Implant Stress

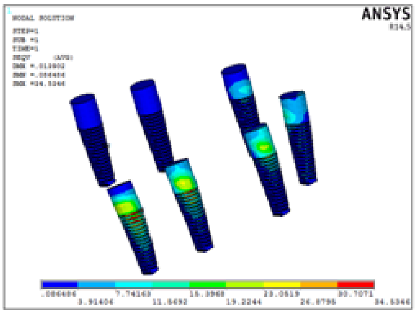

Fig. 5A Implant Stress - Cobalt Chromium Superstructure and Composite Resin Veneer (I)

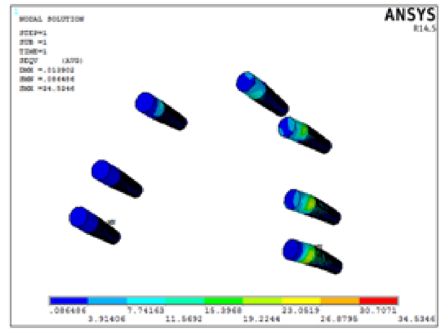

Fig. 5B Implant Stress- Cobalt Chromium Superstructure and Composite Resin Veneer (II)

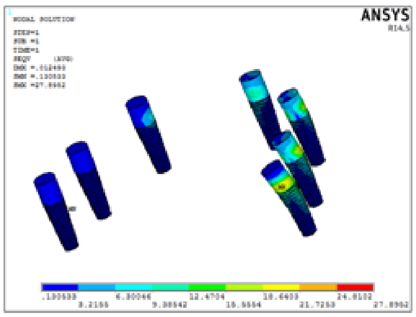

Fig. 5C Stress Distribution in Implants supporting Cobalt Chromium Superstructure and Porcelain Veneer

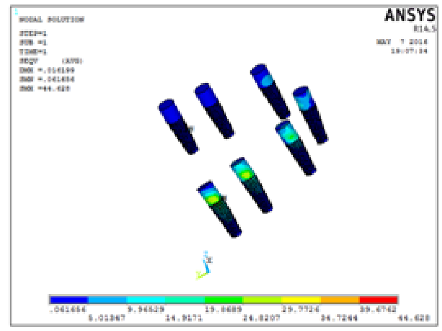

Fig. 5D Stress Distribution in Implant- Titanium Superstructure and Composite Resin Veneer (I)

Implant Stress

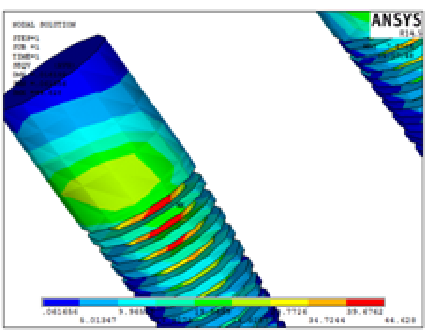

Fig. 5E Stress Distribution in Implant- Titanium Superstructure and Composite Resin Veneer (II)

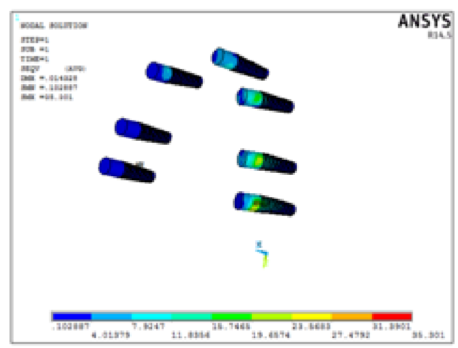

Fig. 5F Stress Distribution in Implants- Titanium Superstructure & Porcelain Veneer

Bone Stress

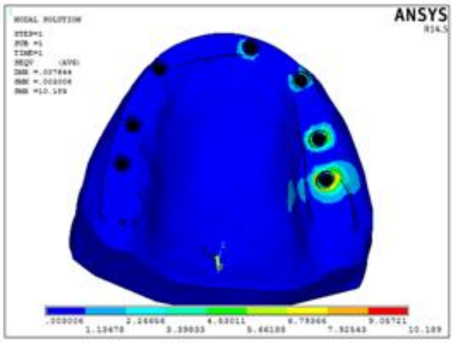

Fig. 6A Bone Stress- Cobalt Chromium Superstructure and Composite Resin Veneer

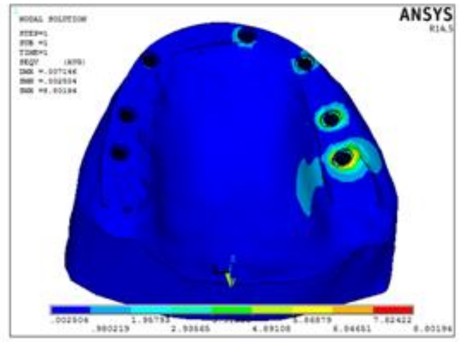

Fig. 6B Bone Stress- Cobalt Chromium Superstructure and Porcelain Veneer

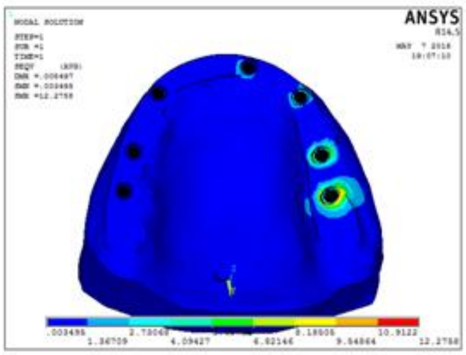

Fig. 6C Stress Distribution in Bone - Titanium Superstructure and Composite Resin Veneer

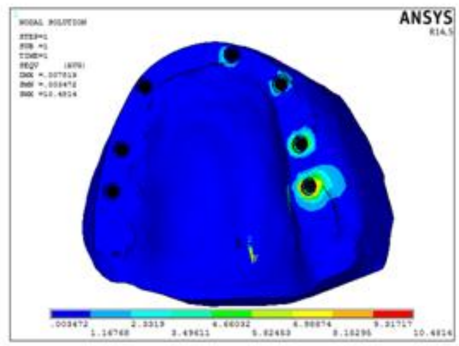

Fig. 6D Stress Distribution in Bone- Titanium Superstructure and Porcelain Veneer

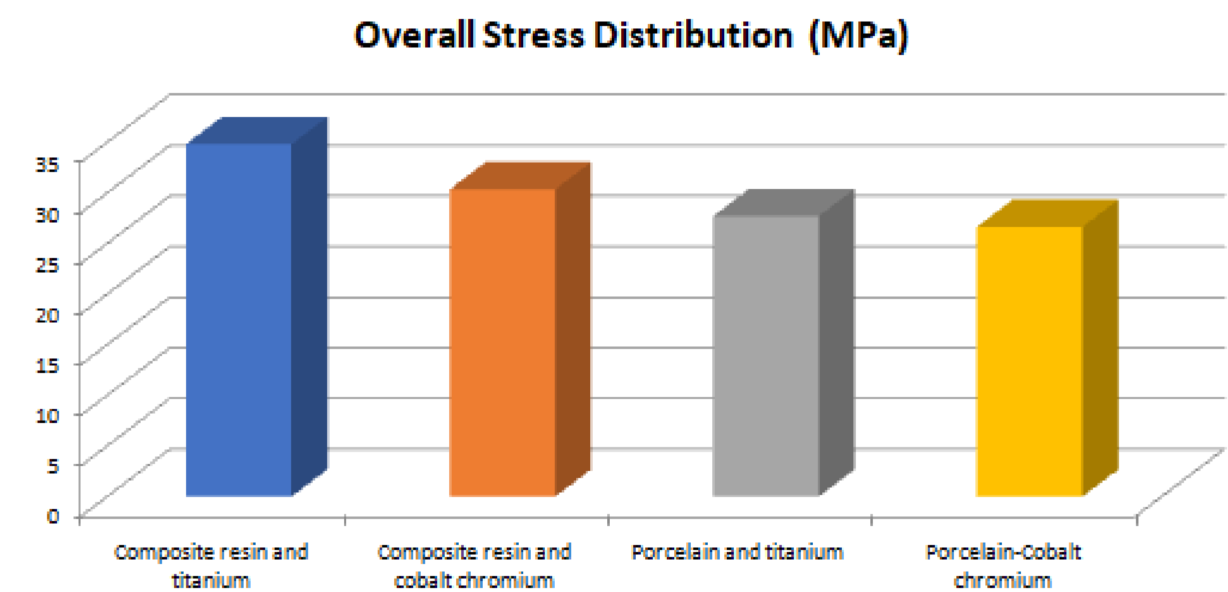

Fig. 7 Graph 1 Overall Stress Distribution Results

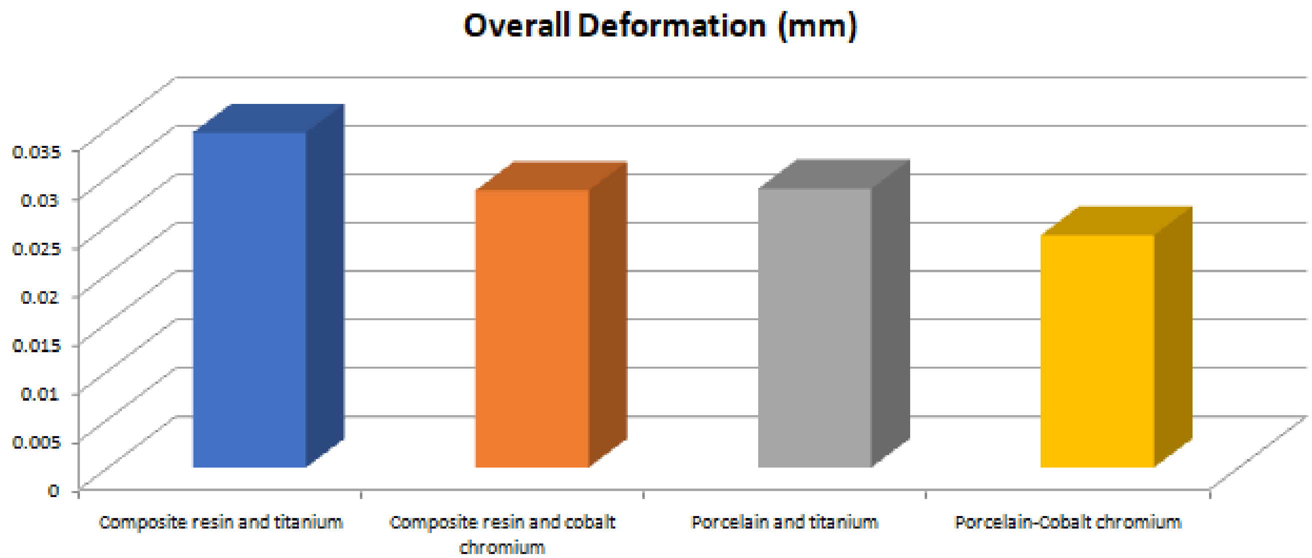

Fig. 8 Graph 2 Overall Deformation

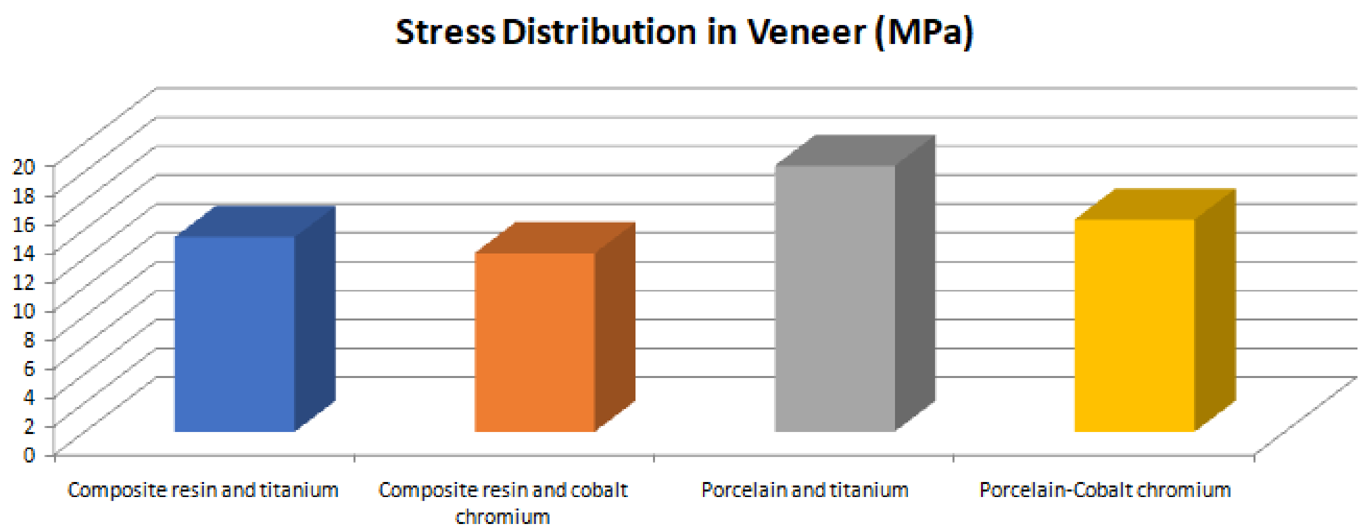

Fig. 9 Graph 3 Stress Distribution in Veneer

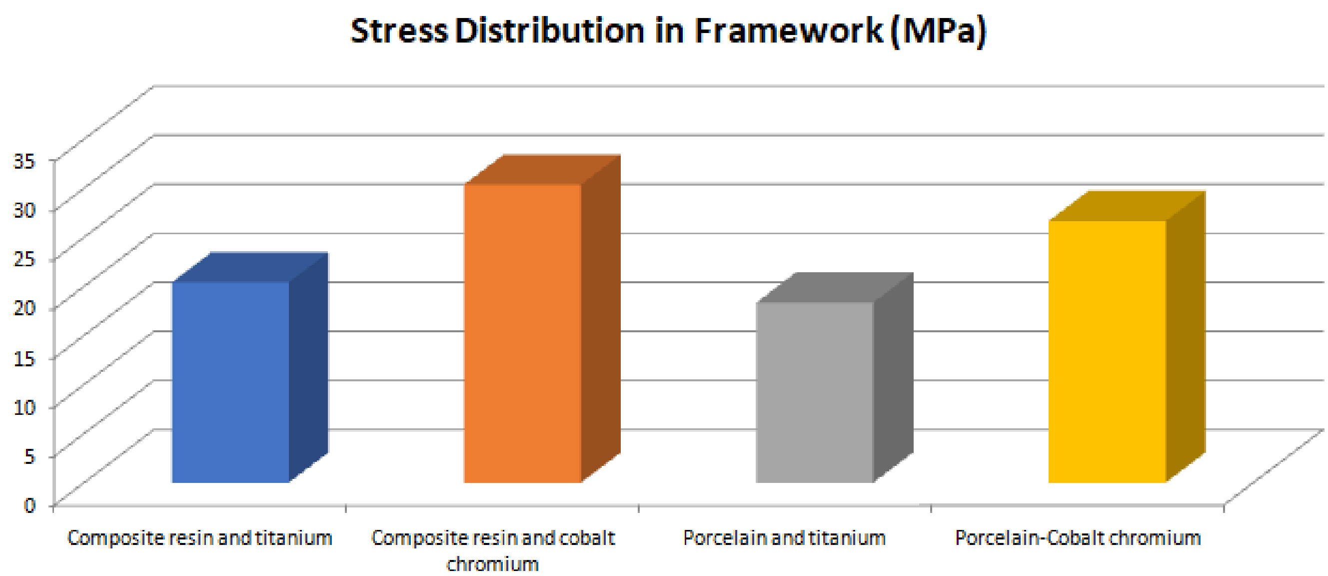

Fig. 10 Graph 4 Stress Distribution in Framework

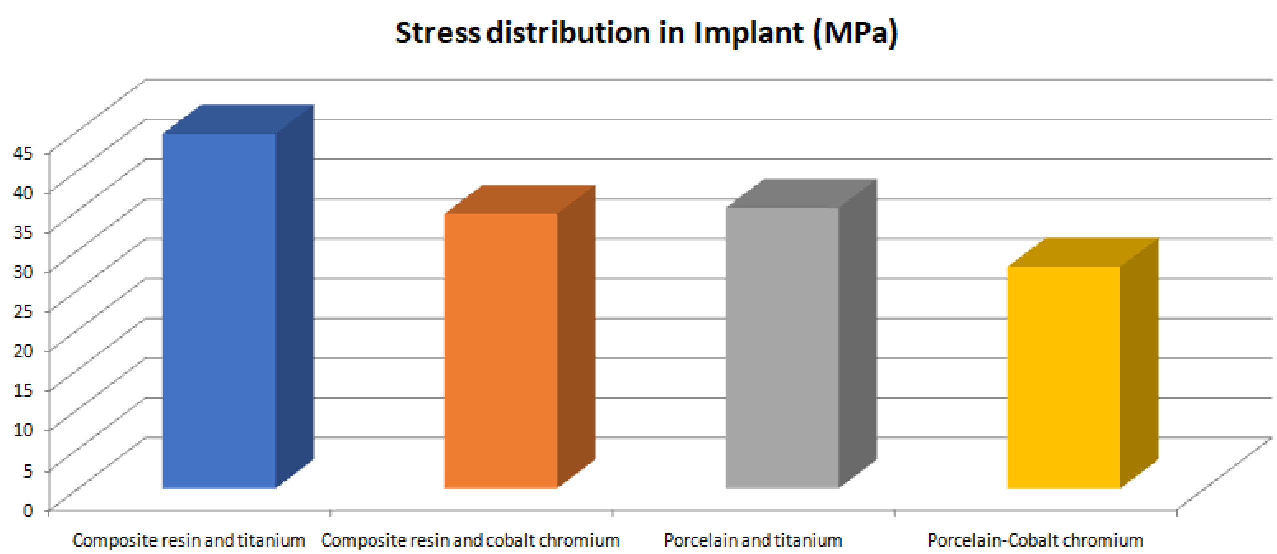

Fig. 11 Graph 5 Stress Distribution in Implant

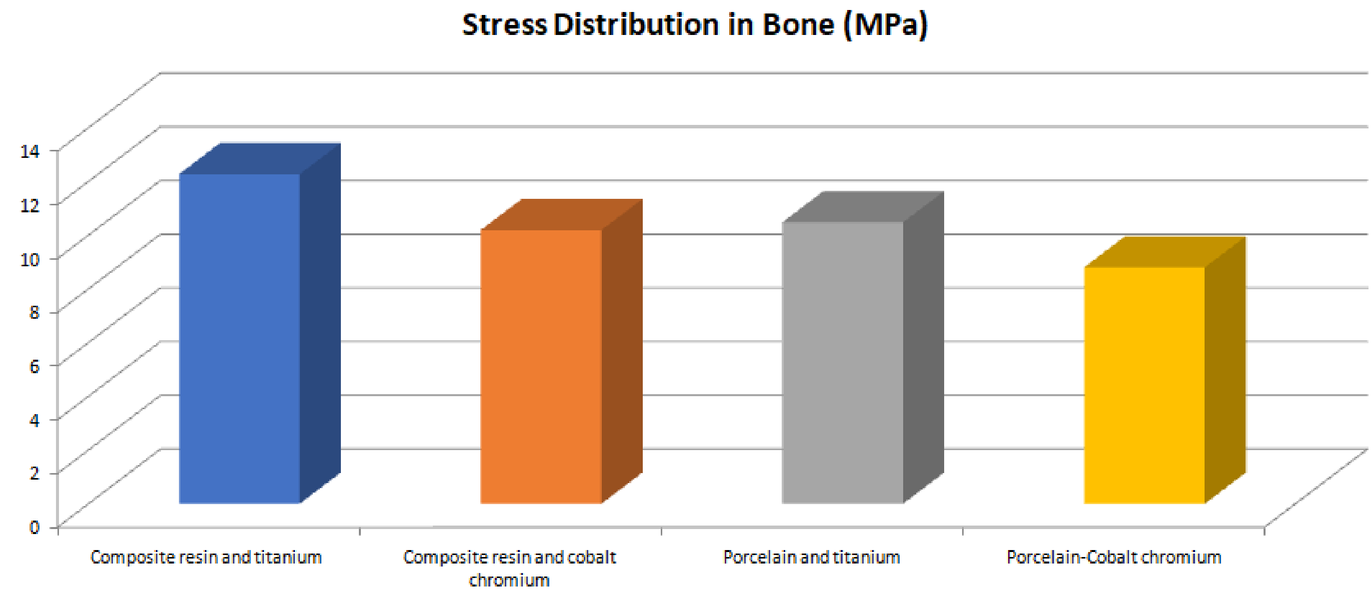

Fig. 12 Graph 6 Stress Distribution in Bone