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Original Research Article

Biomechanical evaluation of four different framework designs of cantilever zirconia resin bonded fixed dental prosthesis: A three-dimensional finite element analysis study

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ABSTRACT

Aim: To measure stress and strain concentrations on four different RBFDP designs and its effect on cement layer and the Periodontal tissues using FEA.

Materials and Methods: Using CBCT data, two 3D models of a maxilla with missing lateral Incisor were printed. Tooth preparation for RBFDP was done. One model had proximal-groove of 4mm and other had 3mm proximal-groove. Four designs of cantilever RBFDPs were designed. Model-1: #21 abutment/ 3x3mm connector; Model-2: #21 abutment/ 3x4mm connector; Model-3: #23 abutment/ 3x3mm connector and; Model-4: #23 abutment/ 3x4mm connector. All Models were converted into FEA models, occlusal force of 200N was loaded at 450 to long axis of pontic and FEA was carried out. Maximum Principal Strain(MPS) in the RBFDP framework, periodontal tissues and Maximum Shear Stress(MSS) in cement layer were measured to evaluate the impact on periodontal tissues and the risk for framework-debonding respectively.

Results: The MPS of framework in decreasing order was: Model-1>Model-2>Model-3>Model-4. The MPS of PDL: Model-1 and Model-2 > Model-3 and Model-4. MSS in cement layer: Model-1 and Model-2 > Model-3 and Model-4. Adhesion area with shear stress >11MPa: Model-1 and Model-2 > Model-3 and Model-4. MPS and MMS values were lower in models with 3×4mm connector than models with 3x3mm connector.

Conclusion: Adequate Connector dimension and adhesion-area are critical for success of RBFDP. Within the limitations of this study, RBFDP design with 3x4mm connector and Maxillary Canine as abutment for replacing Maxillary Lateral Incisor is better option in terms of framework-debonding risk and preservation of periodontal tissues.

1. Introduction

Missing teeth in the anterior region is a common occurrence.[1] Maxillary Central Incisors are most frequently affected teeth by trauma;[2] while Maxillary Lateral Incisors are the most commonly malformed teeth in the anterior region and also the most common congenitally missing teeth bilaterally.[1]

The prosthetic treatment options for single missing anterior tooth include autotransplantation of deciduous or permanent teeth, orthodontic space closure, implants, conventional fixed dental prostheses and resin-bonded fixed dental prostheses (RBFDPs).[1] Single missing anterior tooth

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results in a small edentulous span where it is difficult to justify the extensive reduction of the adjacent teeth to support a conventional fixed dental prostheses (FDP).[3] Implants are also not the choice for all cases. At such times resin-bonded fixed dental prostheses (RBFDP) offer a most viable, minimally invasive treatment option. In a conventional FDP 63%-72% of the tooth structure is lost; while in a RBFDP, the maximum tooth hard tissue loss ranges from 3–30% only.[4]

There are many problems associated with RBFDP treatment concept like unilateral debonding of any one retainer wing;[5] finding a common axis of insertion with respect to the principle of minimally invasive preparation;[6] and thirdly both abutments should have the same mobility, otherwise the weakest may detach from the enamel, compromising the entire restoration.[7] The peeling and the shear forces caused unilateral debonding of the metal RBFDP, but this did not occur with all-ceramic RBFDP as Ceramics were more torsion resistant; instead overloading caused framework fractures in the area of smaller proximal connector.[5] The treatment modality using single retainer RBFDP retainers evolved accidently when unilaterally fractured two-retainer RBFDPs remained in function as a cantilever RBFDP for five or more years.[8] Superior longevity of single retainer RBFDP compared to two-retainer RBFDP has been confirmed by many studies.[9–12]

Designing the connector in anterior FDP is very critical as most failures of all-ceramic restorations reported fracture at the connector region.[13] Maxillary incisors are the most visible teeth, if the connector is too large it can cause periodontal and esthetic problems while smaller size will compromise the strength. A connector cross-sectional area of minimum 5mm2 is recommended for anterior Zirconia FDP.[14,15] Densely sintered zirconia ceramic is one of the strongest all-ceramic materials available today and provides high fracture strength and fracture toughness[16] and therefore might be suitable for the fabrication of cantilevered all-ceramic RBFDPs without a metal reinforcement. In the present study Yttria-Stabilized Tetragonal Zirconia Polycrystals (Y-TZP) is used as the RBFDP framework material.

Improper designing of the prosthesis will also result in defective occlusion and excessive loading of the abutment which in turn will also strain the periodontal ligament (PDL).[17] Excessive strain of the PDL will affect the prognosis of the abutment and overall prostheses. Therefore, considering damage to the PDL seems to be critical for long term prognosis while designing any prosthesis. There is very less literature regarding effect of RBFDP on preservation of periodontal tissues. Hence, in this study different designs of RBFDP are compared by evaluating its effect on the biomechanical behaviour of the periodontal tissues.

The Finite Element Method (FEM) or the FEA, is a method used for solving structural problems with complex geometry under external load.[18] Owing to the complexity of RBFDP, FEA was used to measure stress and strain in the various designs of RBFDP, in the cement layer as well as in the PDL and the Alveolar bone.

2. Materials and Methods

To conduct this study, prior permission was obtained from institutional review Board.

2.1. Three dimensional image generation

Sectional CBCT (Cone Beam Computed Tomography) data of the anterior maxilla with missing left permanent Lateral Incisor #22 (Figure 1) was used to create three-dimensional image using CAD Software (DentalCAD, Exocad GmbH, Germany). The 3D image was converted into two 3D models using 3D printer (ACUUFAB-D1, DLP 3D Printer, Shining 3D, China) with opaque model resin material (Figure 2).

2.2. Teeth preparation

Tooth preparation was done on resin models in relation to #21 and #23. Wing preparation of 0.5 mm thickness was done on palatal surfaces using Wheel-shaped diamond bur (WR-13, Mani Medical India Pvt Ltd). Chamfer margin of 0.5 mm was given 2 mm below incisal edges, 1 mm supragingivally using SO21 bur (Mani Medical India Pvt Ltd). Vertical groove of 1 mm depth were made on proximal surface facing the edentulous area of each abutment teeth using Tapered-Fissure carbide bur (169L, Mani Medical India Pvt Ltd). In one model, length of these grooves was kept as 3 mm; while in the second model it was kept as 4 mm (Figure 3). Three palatal pits of 0.5 mm depth and 1 mm diameter were made forming a triangle using round Diamond Bur (BR-41, Mani Medical India Pvt Ltd) . The models were scanned using 3SHAPE TRIOS Lab Scanner (3Shape, USA) to obtain a 3D-Image with the details of teeth preparation. After obtaining the scanned data, uneven and rough areas in the tooth preparation were modified using 3SHAPE TRIOS DESIGN Studio (3Shape, USA) to maintain symmetry and even thickness for framework material.

2.3. 3D model construction for framework designing

Using the same Sectional CBCT data, both the abutment teeth #21 and#23 were delineated along with the root and the corresponding alveolar socket 3-dimensionally using Imaging Software AIS Software (ACTEON Imaging Suite, Acteon India Pvt. Ltd) (Figure 4). The 3D scanned data of the tooth preparation of both models was substracted, overlapped and merged on this 3-dimensionallay delineated individual abutment teeth. The two 3D models which are obtained now were ready for framework designing.

2.4. Designing of the framework

Four cantilevered RBFDP frameworks (Figure 5) were designed on the obtained 3D models using 3SHAPE TRIOS DESIGN Studio (3Shape, USA) resulting in total four models as follows (Figure 6)

1. Model-1: #21 as abutment and connector of 3 mm × 3 mm
2. Model-2: #21 as abutment and connector of 3 mm × 4 mm
3. Model-3: #23 as abutment and connector of 3 mm × 3 mm
4. Model-4: #23 as abutment and connector of 3 mm × 4 mm

2.5. 3D Model construction for FEA

The ".stl"data of each of the four models was converted into in ".step" format to obtain respective FEA Model using Sodidworks Software (Solid Works 2019, Dassault Systems, USA). All four FEA models were imported to the ANSYS software (ANSYS Workbench R19.3). Boundary of each structure was defined using Design Modeler Software (ANSYS Workbench R19.3). An adhesive Cement layer of 50 μm was defined between the tooth surface and the framework [19] extending in the entire tooth preparartion area. An enamel layer of 120 μm was differentiated in the crown portion of both the abutments. PDL of average 0.2 mm thickness was differentiated surrounding the root surface considering the normal anatomic range of width of PDL [20] as 0.2 to 0.38 mm. Alveolar bone was differentiated into Cortical and Cancellous Bone.

All the materials were considered to be isoptropic, homogenous and linearly elastic. PDL was considered to have Bilinear Elasticity.[21] The Material properties [17] were assigned according to theTable 1.

2.6. Loading conditions

All the established boundary conditions were fixed in all axes (x,y and z). Load of 200 N was given at $45^0$to the long axis of the pontic (Lateral Incisor). 200 N force was considered as the maximum range of occlusal force for the Anterior teeth.[22,23]

The mesh was generated with tetrahedral quadratic elements, allowing the copying of irregular geometry present in the models following which a 3D FEA was carried out in ANSYS software (ANSYS Workbench R19.3).

3. Results

3.1. Principal strain distribution in the zirconia framework (Table 2)

In model-1, maximum principal strain with the highest value was concentrated at the occlusal portion of the connector on the palatal side (Figure 7). In model-2, the highest value of maximum principal strain was located at the center of the lower half of the retainer wing on the side facing the tooth surface (Figure 8). For Model-3, highest principal strain was located at the gingival portion of the connector (Figure 9). In Model-4, maximum principal strain was concentrated in the connector region and the periphery of the retainer with highest value found at distal most portion of periphery of the retainer wing (Figure 10). The average values of maximum principal strain had a decreasing order: highest was in model-1, followed by model-3, model-2 and least in model-4. Framework designs with Connector of 3×4 mm had lower strain values compared to the corresponding designs with 3×3 mm connector dimension.

3.2. Shear stress of the adhesive cement layer (Table 3)

In model-1 and model-2, shear stresses of the cement layer were dispersed covering major adhesion area with the maximum shear stress located in the area of cingulum (Figures 11 and 12). Cement layer in both model-3 had shear stresses concentrated at the periphery of the adhesion area with maximum value located at the distogingival margin (Figures 13 and 14). Maximum shear stresses in cement layer of model-1 and model-2 exceeded the shear stresses in model-3 and model-4. The models with connector of 3×4 mm showed comparatively more shear stress values than the models with connector of 3×3 mm.

The minimum bond strength required for clinical success was found to be 10-11 MPa.[24] In this study, the area of the adhesive cement layer exceeding 11 MPa shear stresses was demarcated (grey areas) to investigate the risk of framework-debonding. In model-1 and model-2, most of the cement area showed shear stresses more than the minimum bond strength recommended (11 MPa) (Figures 11 and 12). In model-3 and model-4, the shear stresses exceeding the 11MPa were concentrated only at the periphery of the adhesion area (Figures 13 and 14). Risk of debonding was very high for model-1 and model-2; while it was comparatively very low for model-3 and model-4.

3.3. Principal strain of periodontal ligament and alveolar bone (Table 4)

Results showed that the maximum principal strain in the PDL of Central Incisor (model-1 and 2) was greater than that of Canine (Model-3 and 4). Principal strain distribution in the alveolar bone (cortical bone) of all four models was almost similar with values in model-3 and model-4 slightly more than that of model-1 and model-2. In model-1 and model-2, the strain concentration pattern was similar with the maximum principal strain concentrated at the cervical portion of the distopalatal surface of the PDL (Figures 15 and 16). In model-3 and moel-4, maximum principal strain in the PDL was concentrated along the palatal surface ( ). Overall, periodontal tissues of model-1 and model-2 showed much higher values of maximum principal strain than that of model-3 and model-4.

Table 1: Material properties [17]

Material	Young's Modulus (MPa)	Poisson's Ratio
Enamel	8.0×10^4	0.30
Dentin	1.50×10^4	0.31
Periodontal ligament	$5.90, 2.45 \times 10$	0.40, 0.49
Adhesive Cement Layer (Panavia F 2.0)	1.50×10^4	0.30
Zirconia (Y-TZP)	2.10×10^5	0.31
Cortical Bone	1.37×10^4	0.30
Cancellous Bone	3.45×10^2	0.31

Figure 1: Sectional CBCT of maxilla

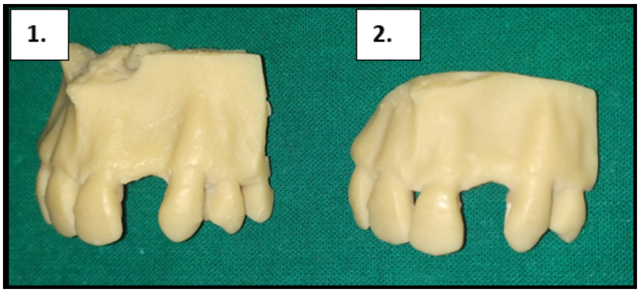

Figure 2: Two 3D printed models using model resin material

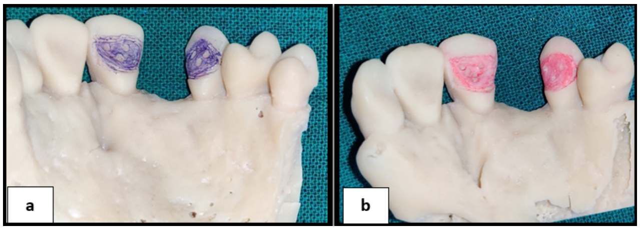

Figure 3: Completed Tooth preparation on both models; **a:** Blue area -Tooth preparation with 3 mm proximal groove length; **b:** Red area - Tooth preparation with 4 mm proximal groove length

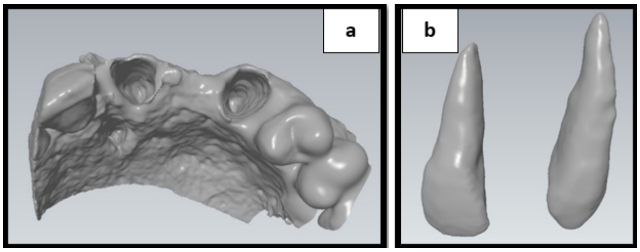

Figure 4: **a:** Alveolar socket delineated; **b:** Individual abutment teeth delineated

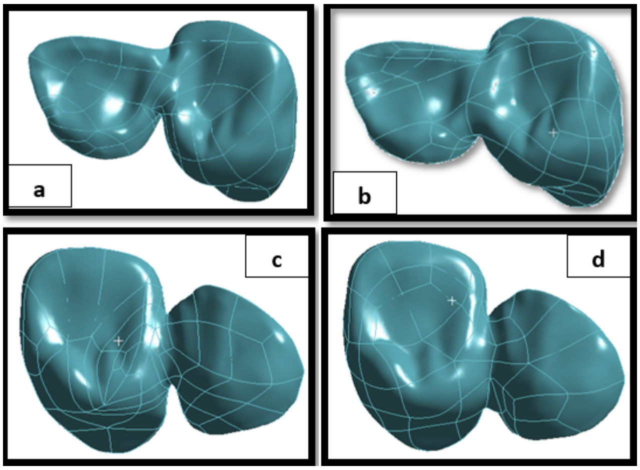

Figure 5: Final framework designs; **a:** Using #21 as abutment and connector of 3*3 mm dimension; **b:** Using #21 as abutment and connector of 3*4 mm dimension; **c:** Using #23 as abutment and connector of 3*3 mm dimension; **d:** Using #23 as abutment and connector of 3*4 mm dimension

4. Discussion

When any prosthesis is loaded by functional forces of mastication, it undergoes some deformation along with deformation of the luting agent as well as displacement of the abutment tooth.[5] If this deformation exceeds a certain amount, it will result in either framework fracture or framework debonding. To study this deformation, maximum Principal strain was investigated for the framework designs and the periodontal tissues and Shear stress distribution was

Table 2: Average values of maximum principal strain distribution for the framework

Type of Design	Model - 1	Model – 2	Model – 3	Model – 4
Average values of Maximum Principal Strain(m/m)	1.97×10^{-4}	1.49×10^{-4}	1.902×10^{-4}	1.26×10^{-4}

Table 3: Maximum shear stress in adhesive cement layer

Type of Design	Model - 1	Model – 2	Model – 3	Model – 4
Maximum value of Shear Stress in Cement Layer (MPa)	386.11	360.88	133.68	166.13

Table 4: Average values of maximumprincipal strain in periodontal ligament and alveolar bone

Type of Design	Model - 1	Model – 2	Model – 3	Model – 4
Maximum Principal Strain in PDL (m/m)	1.68×10^{-1}	1.67×10^{-1}	4.39×10^{-3}	4.15×10^{-3}
Maximum Principal Strain in Alveolar bone (m/m)	8.24×10^{-4}	8.34×10^{-4}	9.41×10^{-4}	9.02×10^{-4}

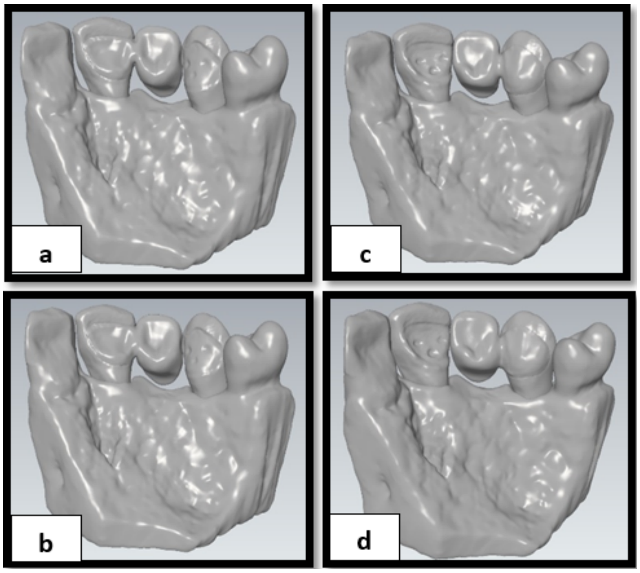

Figure 6: Final assembled Models; **a:** Model-1; **b:** Model-2; **c:** Model-3; **d:** Model-4

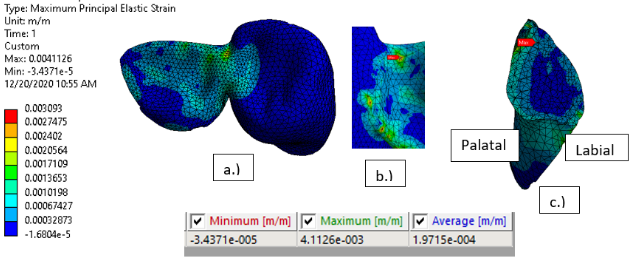

Figure 7: Maximum principal strain distribution in zirconia framework of Model-1; **a:** Palatal view; **b:** Enamel side; **c:** Vertical cross-section at connector

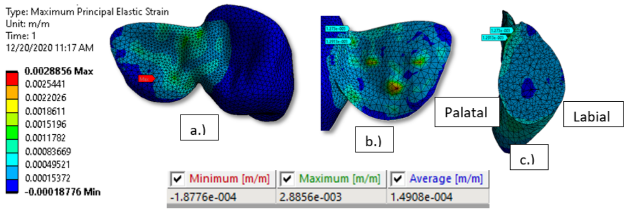

Figure 8: Maximum principal strain distribution in zirconia framework of Model-2; **a:** Palatal view; **b:** Enamel side; **c:** Vertical cross-section at connector

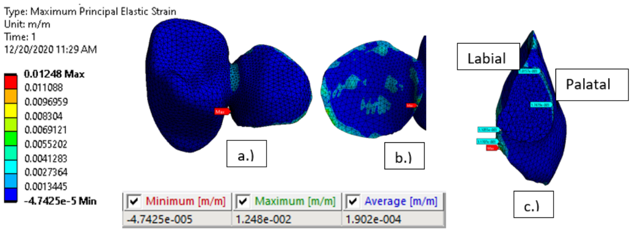

Figure 9: Maximum principal strain distribution in zirconia framework of Model-3; **a:** Palatal view; **b:** Enamel side; **c:** Vertical cross-section at connector.

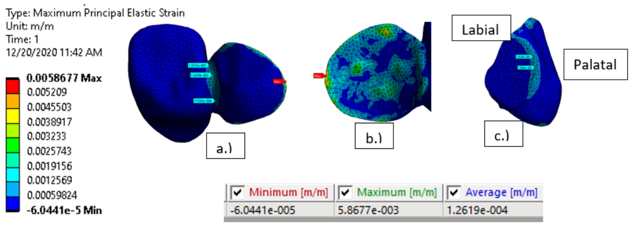

Figure 10: Maximum principal strain distribution in zirconia framework of Model-4; **a:** Palatal side; **b:** Enamel side; **c:** Vertical cross-section at connector

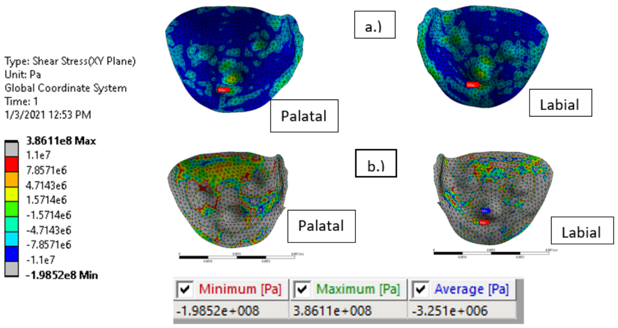

Figure 11: a: Shear Stress distribution in Adhesive cement layer of Model-1; **b:** The voxels having shear stress value >11 MPa in adhesive cement layer (grey area) of Model-1

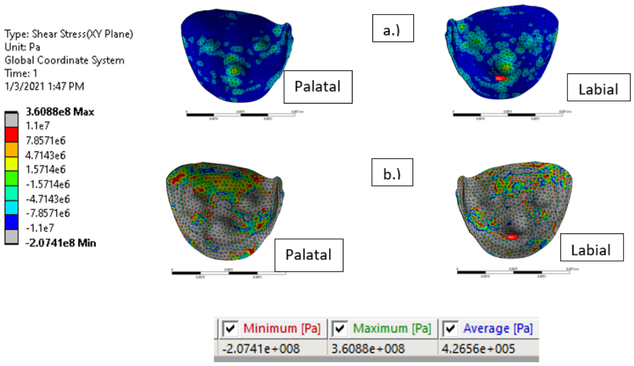

Figure 12: a: Shear Stress distribution in Adhesive cement layer of Model-2; **b:** The voxels having shear stress value >11 MPa in adhesive cement layer (grey area) of Model-2

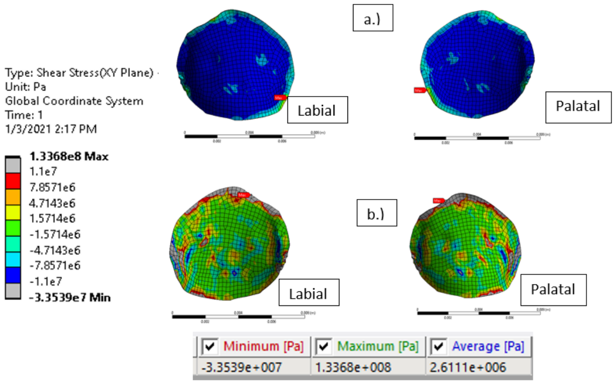

Figure 13: a: Shear Stress distribution in Adhesive cement layer of Model-3; **b:** The voxels having shear stress value >11 MPa in adhesive cement layer (grey area) of Model-3

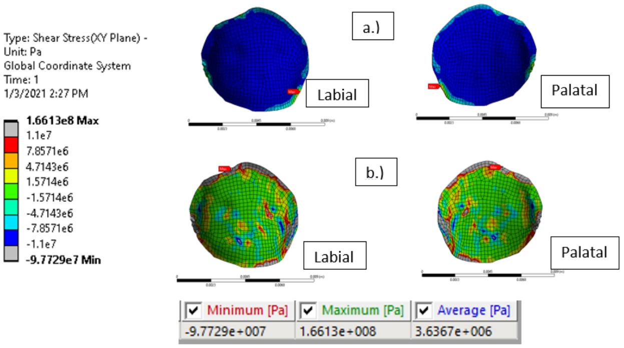

Figure 14: a: Shear Stress distribution in Adhesive cement layer of Model-4; **b:** The voxels having shear stress value >11 MPa in adhesive cement layer (grey area) of Model-4

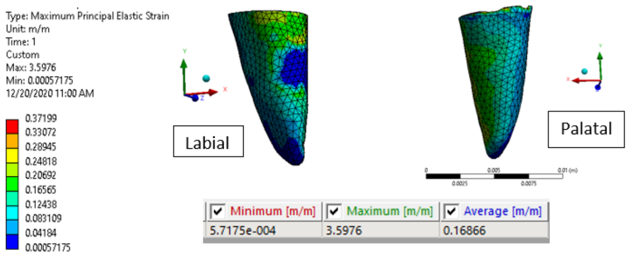

Figure 15: a: Shear Stress distribution in Adhesive cement layer of Model-1; **b:** The voxels having shear stress value >11 MPa in adhesive cement layer (grey area) of Model-4

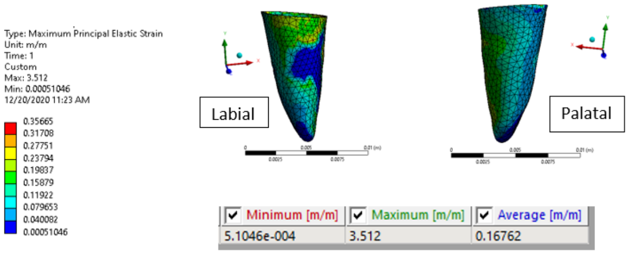

Figure 16: Maximumprincipal strain distribution in PDL and alveolar bone of Model-2

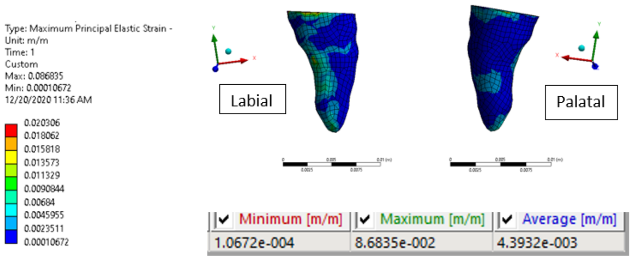

Figure 17: Maximumprincipal strain distribution in PDL and alveolar bone of Model-3

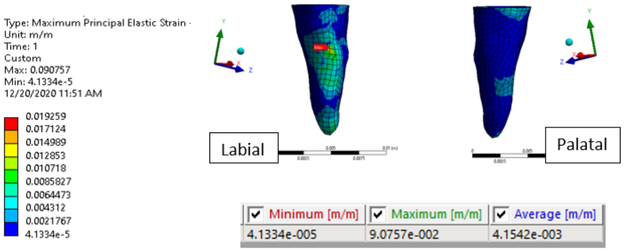

Figure 18: Maximumprincipal strain distribution in PDL and alveolar bone of Model-4

investigated in the adhesive cement layer for four different RBFDP designs. FEA was chosen as analysis method as it enables the visualization of superimposed structures, and the stipulation of the material properties of anatomic craniofacial structures [18,25] and with the advances of digital imaging systems (CT and MRI), it has become possible to extrapolate the individual specific data of bone geometry and property to an FEA model.

4.1. Principal strain distribution in the Zirconia framework

Models with connector dimension 3x3 mm (model-1 and 3) showed more strain than their 3x4 mm counterparts suggesting comparative more distortion of the former. The maximum principal strain in the framework of model-1 was located in incisal portion of the connector and in the framework of model-3, it was located at the gingival portion of the connector. Model-2 and Model-4 with the connector of 3×4 mm, the maximum principal strain of framework was concentrated away from the connector region. This suggested that increased dimension of the connector reduced the strain at the connector region and thus improving the strength. This result was similar to the study done by A. Uraba et al [17] where maximum principal strain in the two-unit cantilevered RBFDPs was found to be concentrated on the palatal side of the connector with either central incisor or canine as abutment. The study by Pospiech P. et al [26] investigated distal cantilevered FDPs with differing cantilever morphologies and found higher stress at the occlusal embrasure of the connector between the pontic and second premolar abutment compared to the cervical embrasure. In another study by Taskonak B. et al, [27] the occlusal and gingival embrasures of connectors were reported to be the areas of highest stresses suggesting an increase in connector dimension at respective areas.

As the cantilevered RBFDPs have single fixed support, the displacement of the abutment will decide the distortion of the corresponding framework. The frameworks with #21 as abutment showed more distortion than the frameworks with #23 as abutment indicating that the displacement of Central incisor was more compared to Canine. This results also agreed with the study done by A. Uraba et al [17] where the cantilevered framework was more distorted on the central incisor side than on the canine side.

4.2. Shear Stress Distribution around adhesive Cement layer

Adhesive cement layer is the connecting interface between the zirconia framework and immediate enamel layer. Under functional loading, peeling force is generated at the adhesive interface that can cause debonding of the framework. This can be investigated by studying shear stress distribution.

The minimum bond strength required for clinical success was found to be 10-11 MPa. [24] To calculate the risk of debonding, the volume of the cement layer where shear stresses were exceeding 11MPa was demarcated (Grey areas in Figures 15, 16, 17 and 18). Model-1 and model-2 had major area of stresses exceeding 11MPa compared to model-3 and model-4. This indicated that destruction of the adhesive cement and consecutive risk of framework debonding in the designs with central incisor as abutment was more severe than in the designs with canine as abutment. Adhesion area also plays critical role in obtaining adequate bond strength. Here, the adhesion area for retainer wing on central incisor was 78 mm^2 which was less than canine having 87 mm^2 of adhesion area and thus more shear stresses were on central incisor designs (model-1 and 2). In the study by A. Uraba et al [17] central incisor had the adhesion area of 103 mm^2 and canine had 75 mm^2 adhesion area. In their study, the shear stress of the adhesive cement was smaller in the central incisor design than that of canine. This suggested that regardless of tooth type for the abutment, it may be necessary to increase the adhesion area to reduce the risk for framework-debonding.

Models with 3x4 mm connector (model-2 and 4) had less shear stress in the cement layer compared to 3x3 connector designs (Model-1 and 3). Thus teeth accommodating a vertical groove spanning the length and width of the tooth are better able to maintain a sufficient adhesion area, and should be chosen as the abutment tooth. Study by Nair A. et al [28] also showed that placement of the grooves increased the retention values by almost $2\frac{1}{2}$ times than the grooveless preparation.

4.3. Maximum principal strain in periodontal ligament

Under occlusal loading, stress accumulation occurs in PDL also. The maximum principal strain in the PDL of model-1 and model-2 was higher than model-3 and model-4. This result can be correlated with the average periodontal ligament volume of individual abutment tooth. Canine is a longer tooth compared to Central Incisor having more surface area of the PDL. In the present study, the surface area of PDL of #21 measured was 308 mm^2 while that of PDL of #23 was 332 mm^2. Corresponding to this, model-

1 and model-2 with central incisor as abutment having less PDL volume had more strain indicating that Central incisor undergoes more distortion than canine under functional loading. When considering protection of PDL, Canine can be considered as a better abutment. Similar results was found by Uraba et al [17] in 2017.

In the present study, the simulated FEA model obtained from CBCT data was of optimum criteria in terms of PDL and Alveolar bone level. Study by Erika Sukumoda et al [29] investigated the risk of debonding of resin-bonded fixed dental prosthesis frameworks and the effects on the periodontal tissue in patients with reduced alveolar bone levels. They found that the stress concentration of the periodontal tissue will be higher when the alveolar bone level reduction is more than one-third of the root length and consecutive risk of framework debonding will also be higher.

Selection and designing of the prosthesis should be done such that there is minimal damage to the periodontal tissues and while selecting a better abutment for cantilever RBFDP, existing periodontal condition of the prospective abutments should be evaluated clinically as well as radiographically to affirm long term prognosis.

5. Conclusion

Within the limitations of the study, following conclusions can be drawn from this study:

1. When comparing the stress and strain analysis in framework designs, in adhesive cement and on the PDL, Canine was a better abutment than Central incisor in all three aspects for replacing maxillary lateral incisor with a cantilever all-ceramic RBFDP.
2. Increasing the connector dimension from 3×3 mm to 3×4 mm in anterior region, there was decrease in strain on the connector and hence increase in its fracture resistance.
3. Tooth preparation area should have adequate resistance and retention features and maximum adhesion area for a good bond strength and longevity.
4. Abutment tooth with more voluminous periodontal tissue coverage, alveolar bone support and with more clinical crown height will be a better abutment for anterior cantilever RBFDP.

The results of this study helps to choose appropriate abutment for cantilever anterior RBFDP for single missing tooth. As connector is the weakest portion, maximum possible connector dimension as allowed by esthetics should be used for the framework design to preclude fracture of anterior all-ceramic prosthesis. Cantilever RBFDP for replacing missing single anterior teeth can be an excellent minimally invasive treatment alternative to conventional FDP and Implant therapy for small edentulous span for selected cases. Long term Clinical studies are required to confirm the same considering various intraoral occlusal conditions.

6. List of Abbreviations

FEA- Finite Element Analysis; FEM- Finite Element Modelling; RBFPD- Resin Bonded Fixed Partial Denture; RBFDP- Resin Bonded Fixed Dental Prosthesis; RBB- Resin Bonded Bridge; FPD- Fixed Partial Denture; FDP- Fixed Dental Prostheses; 3D- Three Dimensional; CAD-CAM- Computer Assisted Designing and Computer Assisted Machining; .stl- Standard Triangle Language / Standard Tessellation Language; .dicom- Digital Imaging and Communications in Medicine; .step- Standard for the exchange of Product Model Data; 3 mm × 3 mm-3 mm Height and 3 mm Width; 3 mm × 4 mm-3 mm Height and 4 mm Width; CBCT- Cone Beam Computed Tomography; Y-TZP- Yttria-stabilized Tetragonal Zirconia Polycrystal; PDL- Periodontal Ligament; N- Newton; mm- Millimeter; μm- Micrometer; Pa- Pascal; MPa- Mega Pascal; GPa- Giga Pascal; MPS- Maximum Principal Strain; MSS- Maximum Shear Stress; MRI- Magnetic Resonance Imaging; CT- Computed Tomography.

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8. Conflict of Interest

None.

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