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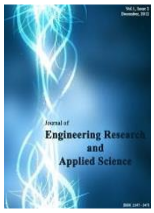

3D FEA of different post systems and cements in a maxillary incisor

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Abstract

The effect of different post materials and cement rigidity on an endodontically treated maxillary central incisor was evaluated in this study by three dimensional stress analyses using the Finite Element Method. Methods: A 3D FEM model of a central maxillary incisor with no surviving dentinal walls was created. The following parameters were studied: 3 loading conditions[mastication, bruxism and impact], 3 different luting cements [Zinc phosphate cement, resin cement with low modulus, resin cement with high modulus], 4 post materials when present [steel, titanium, glass fiber, zirconium posts with composite cores and composite restoration without post]. To standardize the results of the analysis, 22 different points were defined on the model and their analytical positions were determined. Results and conclusion: There were significant differences between post systems and also between cements. The stresses decreased with the post material in order of steel, zirconium, titanium, glass fiber with low modulus adhesive cement. The stresses decreased in order of glass fiber, titanium, zirconium, steel with high modulus adhesive cement. In functional loading, maximum equivalent stress mostly occurs at the vestibular side of the cement layer. Minimum stress values were obtained with the glass fiber post bonded with an adhesive resin cement with low elastic modulus.

Keywords: dental material, post, finite element analysis, stress

1. Introduction

Special care is indicated when selecting the most efficient way to restore endodontically treated teeth because they have a higher risk of biomechanical failure than vital teeth [1-5]. The fracture resistance of post-restored teeth has been the subject of numerous in vitro and in vivo studies [6-45]. A theoretical method for calculating stress distribution within complex structures is the finite element analysis which allows the investigator to evaluate the influence of model parameter variation once the basic model have been correctly defined [43].

FE analysis can be performed with 2 dimensional [2D] and 3 dimensional [3D] models, and the consensus is that the results obtained with 3D models are more valid but also are more time-consuming and costly than 2D models [6,7]. It is possible to mechanically characterize not only enamel and dentin but also bone tissues, periodontal ligament and adhesive interfaces using three dimensional solid elements. Different loading conditions can be evaluated with FEA in order to evaluate stress and strain distributions within teeth and restorations and hypothesize predictive areas under risk of clinical failure [43,49].

The aim of this study was to analyze the stress distribution in a 3D FEM model of a central maxillary incisor restored with 3 different luting cements and 4 different post materials under 3 different loading conditions, at 22 standardized analytical points.

2. Materials and methods

The solid model was generated using literature data and the dimensions of the tooth were modeled according to ideal shape of a central incisor [Dental Morphology]. A 3D FEM model of a central maxillary incisor and surrounding structures was generated by ANSYS software [Ansys, Inc. Houston] using IGES format. The volumes were redefined in the new environment and meshed [85326 elements, 148787 nodes] [Figure 1]. Mechanical properties of each component used in this study were summarized in Table 1.

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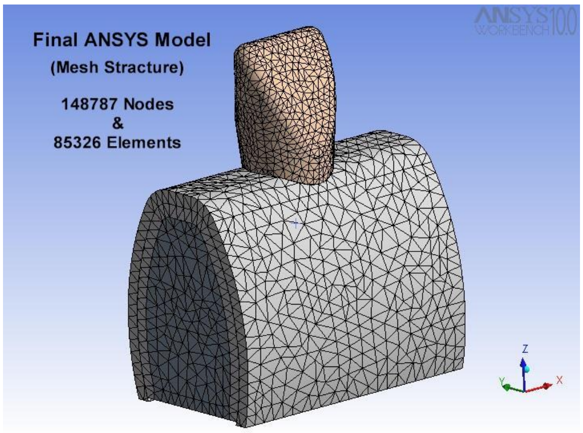


Figure 1: 3D mode lo fmaxillary central incisor.

The teeth were constructed with 5 different techniques: Group 1: Steel post with composite core; Group 2: Titanium post with composite core; Group 3: Glass fiber post with composite core; Group 4: Zirconium post with composite core; Group 5: Composite restoration without post.

Table 1: Mechanical properties used in this study.

Material	Elastic modulus [Gpa]	Poisson ratio	References
Enamel	41	0,30	1
Pulp	0,002	0,45	1
Dentin	18,6	0,31	1,2
Periodontal Ligament	0,0689	0,45	2
Cortical bone	13,7	0,30	1,2
Spongiose bone	1,37	0,30	1,2
Gingiva	0,003	0,45	2
Gutta percha	0,00069	0,45	1
Porselain crown	120	0,28	4
Seramik	69,0	0,28	13
Metal	77,0	0,33	13
Composite core	12,0	0,30	7,8
Titanium post	112	0,33	5
Glass fiber post	40	0,26	4,8
Carbon fiber post	125	0,25	4
Zirconium post	200	0,33	6
Steel post	210	0,30	9
Zinc phosphate cement	22,0	0,35	9
Resin cement [low modulus] []	7,0	0,28	9
Resin cement [high modulus]	18,6	0,28	9

Three luting cements with different elastic moduli were discussed: Zinc phosphate cement, resin cement with low modulus, resin cement with high modulus
The structural efficiency of restorations have been evaluated under 3 different loading conditions 1-100 N force inclined at 135 ° with respect to the tooth axis 2 mm below the incisal edge in order to simulate mastication loads, 2-100N vertical pressure in order to simulate axial loads, 3-100N horizontal force to simulate an accidental impact force.

To standardize the results of the analysis, 22 different points were defined on the model and their analytical positions were determined [Table 2, Figure 2].

Table 2: Schematic of tooth model and local coordinate system.

	X	Y	Z
A	10	15	-7,5
B	10	15	-6,6
C	10	15	-6,5
D	10	15	-5
E	10	15	-4,9
F	10	15	-3,6
G	10	15	-3,5
H	10	15	-2
İ	10	15	-1,9
J	10	15	-1
K	10	10	-7
L	10	10	-5
M	10	10	-4,9
N	10	10	-3,6
O	10	10	-3,5
P	10	10	-1,5
Q	10	5	-6
R	10	5	-4,8
S	10	5	-4,7
T	10	5	-3,8

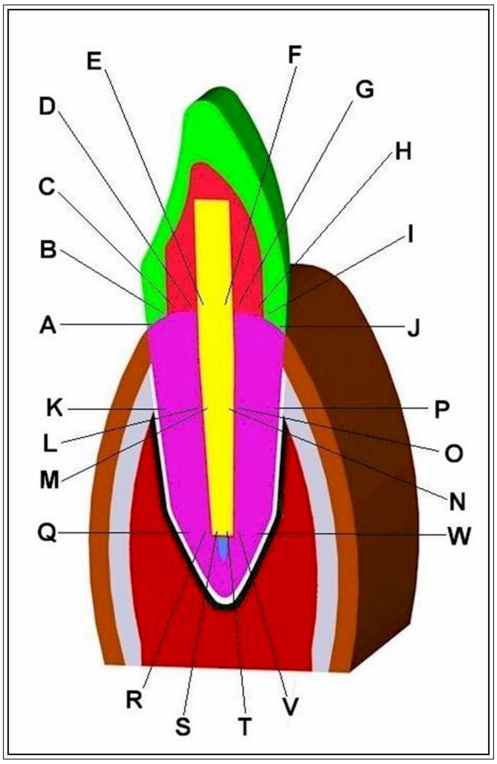


Figure 2: Schematic of tooth model and local coordinate system.

To control the validity of the FEM model, twenty five recently extracted caries free, human maxillary central incisors with similar root sizes were divided into 5 groups. In group 1 the canal of each tooth was restored with glass fiber post [Postec, Vivadent, Schaan, Liechtenstein] and resin cement [Variolink II, Vivadent, Schaan, Liechtenstein] according to manufacturer's instructions. In group 2 the canal of each tooth was restored with zirconium post [Cosmopost, Vivadent, Schaan, Liechtenstein] and resin cement [Variolink II Vivadent, Schaan, Liechtenstein] according to manufacturer's instructions. In group 3 stainless steel posts [Obtur. Screws, FKG Dentaire, La Chaux de Fonds, Switzerland. Lot no:2904] were applied with zinc phosphate cement [Adhesor, Spofa Dental, Praha, Czech Republic Lot no: 1544813-1]. In group 4 no post was applied in the canal. The cores were constructed with light cured composite [Te-Econom, Vivadent, Schaan, Liechtenstein Lot no: G28736]. In group 5 natural teeth without restorations were used as control. Porcelain fused to metal crowns [VMK-95 Metal Keramik; Vita Zahnfabrik, Bad Sackingen, Germany] were constructed and cemented with zinc phosphate cement [Adhesor, Spofa Dental, Praha, Czech Republic Lot no: 1544813-1]. The specimens were tested with universal testing machine [Testometric Micro 500, Testometric Company Ltd., Lancashire, United Kingdom]. Each sample was mounted in a custom made device to ensure that the force was applied at the specific angle. The load was applied 2 mm from the incisal edge of the crown on the palatal side at an angle of 90 degrees to the long axis of the tooth with a crosshead speed of 0, 5 mm/min. Failure threshold was defined as the point fracture occurred. The mode of failure was recorded for each specimen.

Failure loads were analyzed with 1 way analysis of variance [ANOVA] and Scheffe multiple comparison with a significance level of $p<.05$.

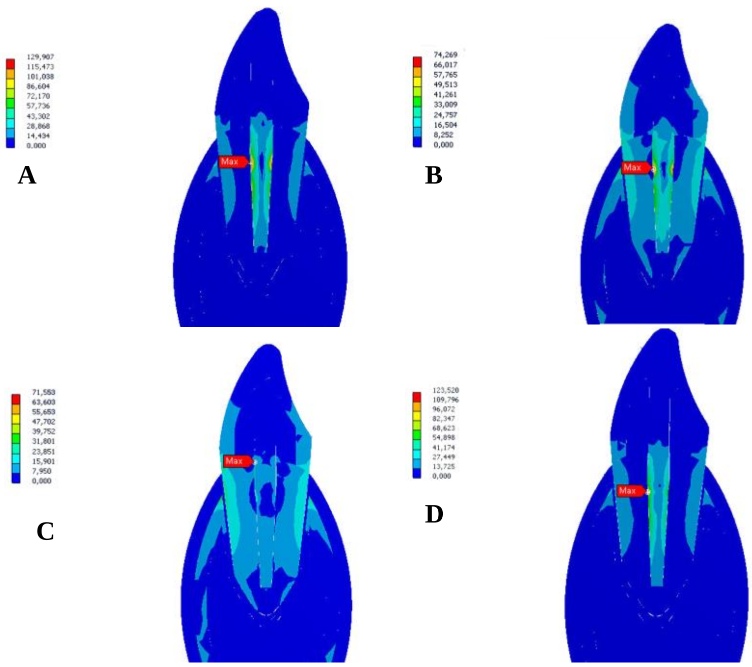
3. Results

Under functional loading the stress reaches a maximum value of 129,9 for the steel post while it reaches a significantly lower value of 71,55 for glass fiber posts cemented with dentine like cements [low elastic modulus]. The stress reaches a maximum value of 136,16 for the steel post while it reaches a higher value of 143,11 for glass fiber posts cemented with softer cements [high elastic modulus]. The stress was found to be 123,52 for zirconium posts cemented with dentine like cements [low elastic modulus] and 136,27 for glass fiber posts cemented with softer cements [high elastic modulus] [Table 3, Figure 3]. Glass fiber posts exhibited the lowest stress values in the cervical part [Point f], middle part [Points m,n] and apical part of the post [Points s,t] in all loading conditions. [Figure4-6]. Steel posts exhibited higher stress values at the middle part of the root than glass fiber and titanium posts with all types of cements and under all loading conditions.

The stresses decreased in order of glass fiber, titanium, zirconium, steel with high modulus adhesive cement. There was a significant difference in the stress distribution at dentin interfaces for the glass post restored tooth cemented with materials of different rigidity. Minimum stress values were obtained with the glass fiber post bonded with an adhesive resin cement with low elastic modulus in all loading conditions [Figure3].

Figure 3: Effect of post material bonded with adhesive cement [low] under functional loading:

A: Steel post, B: Titanium post, C: Glass fiber post, D: Zirconium post



Figures 4-6 show the stress patterns for the various post restorations considered here. The figures are grouped for each loading condition. Glass fiber restored system ensured enough uniformity of stress level. It can be seen that the stress values in the post become less uniform as the stiffness of the post increases. The stress value at the middle of the steel post is 5 times as large as the stress at the glass fiber post. Steel posts and traditional cements, being no adhesive and also more rigid than fiber posts and resin cements, do not allow a homogeneous stress distribution.

Critical areas of high stress concentration are the restoration-cement-dentin interface both in the root canal and on the buccal and lingual aspects of the tooth-restoration interface. Regions of maximum stress changed for the different loading conditions. In functional loading, maximum equivalent stress mostly occurs at the vestibular side of the cement layer [interface between post and cement]. As expected, in the bruxism case, the stress near the post apex is higher than the other loading conditions. The stress values on the buccal aspect are higher in horizontal loading [Figure 4-6].

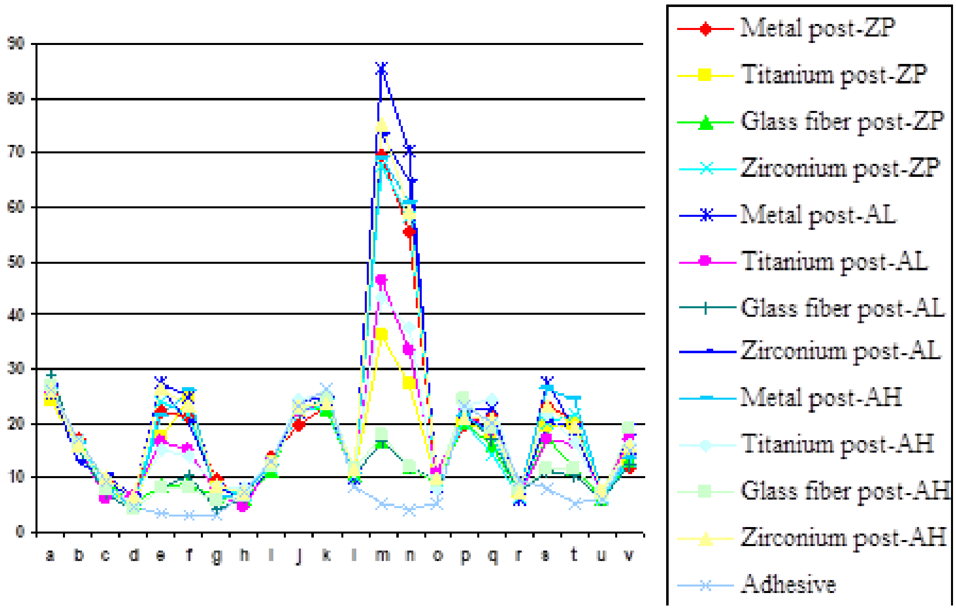


Figure 4: Effect of post material and cement in a model with 2 mm remaining dentinal walls under functional loading.

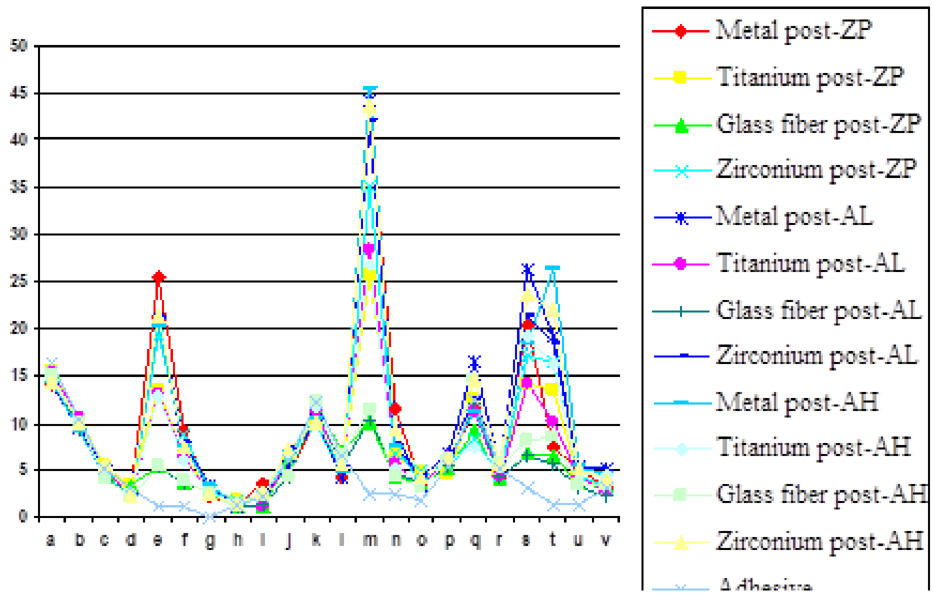


Figure 5: Effect of post material and cement in a model with 2 mm remaining dentinal walls under vertical loading.

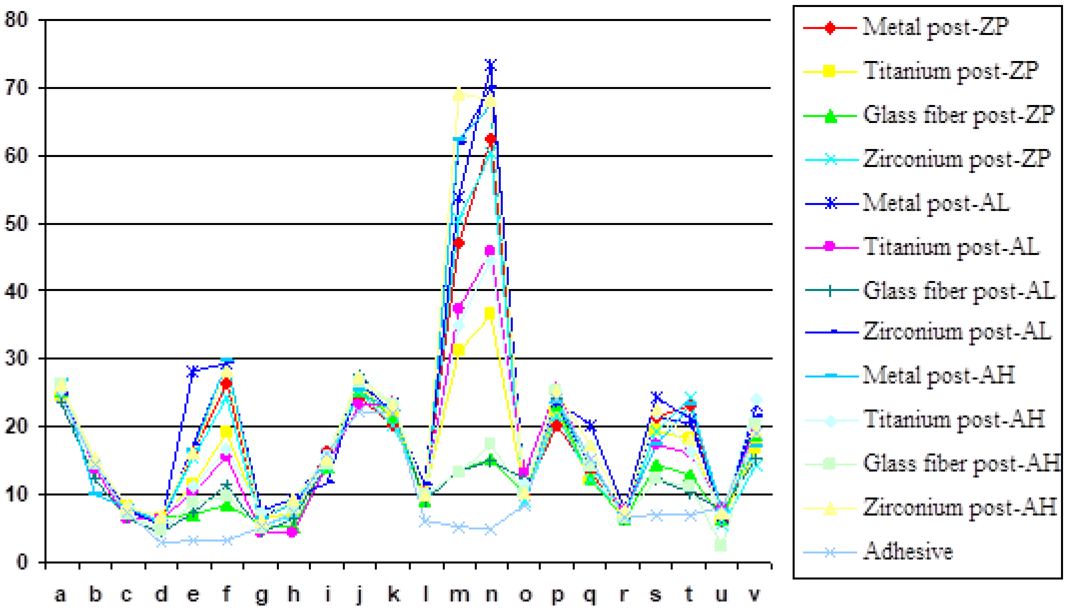


Figure 6: Effect of post material and cement in a model with 2 mm remaining dentinal walls under horizontal loading

Means and standard deviations of failure loads of the fracture test are listed in Table 3-4. The highest fracture strengths were observed in groups restored with glass fiber posts. The mean failure load for this group was 376,38 ± 13,35 N. The results of the ANOVA and Scheffe multiple comparison are presented in Tables 5 and 6. In the fracture strength test, the specimens from Group 1 [glass fiber post] exhibited significantly [$p \leq 0.05$] higher strengths when compared with Group 2 [zirconium] and Group 5 [control]. Group 2 [zirconium] exhibited the lowest strength values [238,98 ± 37,65 N].

Table 3: Effect of post material, cement and loading.

		135	Vertical	Horizontal
Zinc Phosphate cement	Metal post	147,04	58,01	147,93
	Titanium post	281,65	54,43	150,16
	Glass fiber post	154,95	56,66	155,83
	Zirconium post	147,15	55,45	148,05
Adhesive cement low	Metal post	129,9	58,94	132,77
	Titanium post	74,26	34,94	75,8
	Glass fiber post	71,55	25,77	72,3
	Zirconium post	123,52	56,33	126,41
Adhesive cement high	Metal post	136,16	58,12	137,1
	Titanium post	138,38	50,27	139,38
	Glass fiber post	143,11	52,02	144,16
	Zirconium post	136,27	55,56	137,22
Adhesive restoration		40,56	17,28	40,17
		135	Vertical	Horizontal
Zinc Phosphate cement	Metal post	147,04	58,01	147,93
	Titanium post	281,65	54,43	150,16
	Glass fiber post	154,95	56,66	155,83
	Zirconium post	147,15	55,45	148,05
Adhesive cement low	Metal post	129,9	58,94	132,77
	Titanium post	74,26	34,94	75,8

Modes of failure are illustrated in Table 3. There were distinct differences in failure patterns between teeth restored with glass fiber posts and those restored with metal and zirconium posts. One of the teeth in Group 1[glass fiber post] fractured in the apical portion of the root and all the other teeth in this group fractured in a horizontal pattern through the facial side at the cervial part of the crown. All the teeth in Group 2 [zirconium] fractured in a horizontal pattern through the facial side at the level of cementoenamel junction. In Group 3 [metal] all the teeth experienced a horizontal fracture at the middle and apical parts of the root and none of the metal posts fractured. In Group 4 [core] all the restorations experienced a bond failure at the junction of the tooth and the composite core.

Table 4: Fracture loads of the groups [means and standard deviations].

Group	Mean	Standard Deviation
Glass Fiber	376,38	13,34942
Zirconium	238,98	37,65152
Metal	311,2	29,24073
Adhesive	355,94	50,49528
Control	262,56	8,92401

4. Discussion

The 3D FE analysis, showed significant changes in the stresses induced in the tooth-restoration complex when the investigated parameters were varied. It is possible to mechanically characterize not only enamel and dentin but also bone tissues, periodontal ligament and adhesive interfaces using three dimensional solid elements and different loading conditions can be evaluated

Adhesive interfaces of bonded restorations transmit and distribute occlusal forces to the remaining tooth structures homogeneously and increasing the resistance to fracture [50]. On the other hand, the interfaces of materials with different moduli of elasticity represent the weak point of a restorative system, as the toughness mismatch influences the stress distribution [51]. A post with biomechanical properties to those of dentin could be advantageous by reducing the risk of root fractures of teeth. A very stiff post working against the natural function of the tooth creates zones of tension and shear both in the dentine and at the interfaces of the luting cement and the post [43]. In this study minimum stress values were obtained with the glass fiber post bonded with an adhesive resin cement with low elastic modulus.

Glass and carbon posts exhibit high fatigue and tensile strength, and they have a Young's modulus comparable to dentin's [31]. Moreover, these posts can be bonded in root canal with adhesive resin cement. Bonding agents transmit stress between the post and the root structure, reducing stress concentration and preventing fracture [26,42]. Bonding between the post and the cement and between the cement and the dentin appears an important parameter to achieve optimal behavior of endodontical restorations. On the contrary steel post and traditional cements does not allow a homogeneous stress distribution. In this study increased elastic modulus of the dowel was found to cause decreased dentin stress. This result is in agreement with the earlier in vitro investigations [32,42-44]. The FE study of Pegoretti et al [33] concludes that glass fiber dowel resulted in lower stresses inside the root than did the carbon and metal dowel. Isidor and Brondum [12] and Isidor et al [23] found that teeth restored with a carbon fiber dowel were more resistant to fracture than teeth restored with a titanium dowel. Several in vitro studies have determined the resistance to fracture of post restored teeth under static loading and found smaller [18,20] the same [27,38] or higher [30] strength of teeth restored with fiber dowels than teeth restored with metal dowels.

The maximum shear stresses were found to be primarily located at post, cement, dentin interface. Dentin-bonding systems will provide bond strengths, generally in the range of 15 to 30 Mpa [26,43], and posts luted with zinc-phosphate cement have been reported to lose retention at a stress level of approximately 5 to 25 MPa. Cohen et al [15] reported that micromovement of a cemented dowel results in disintegration of the cement and the concentration of stress at the apical end of the dowel over time. The fracture strength of dental cements is less than that of dentin or dowel material. Thus, failure of the system usually occurs cohesively within the cement or at its interface with dentin. Critical areas of high stress concentration were the restoration-cement-dentin interface both in the root canal and on the buccal and lingual aspects of the tooth-restoration interface.

There was a significant difference in the stress distribution at dentin interfaces for the post restored tooth cemented with materials of different rigidity. Under functional loading the stress reaches a maximum value of 71,55 for glass fiber posts cemented with dentine like cements [low elastic modulus] and of 143,11 for glass fiber posts cemented with softer cements [high elastic modulus]. The results lead to the conclusion that the more flexible the posts are, the less rigidity of the cementing medium is relevant. In this study there was difference between the stress values of posts bonded with different cements. Clinically both carbon and glass posts are subjected to debonding and loosening phenomena [43]. Tough cement systems could improve the restoration reliability by opposing to mechanical progression of failure and crack growth.

When the post restored maxillary incisors were evaluated [28,29], the load has been always applied on the palatal aspect in an area ranging from 2 to 3 mm from the incisal margin. This was due to the gnatologic role of incisors, designed to bear non axial loads rather than axial forces. The area of load application coincides with the area of incisor guidance during stomatognatic functions. In this study load was applied 2mm below the incisal margin at the palatinal surface.

Recently, several papers supported the use of a direct restoration without placing any post for restoring endodontically treated teeth [54-56]. Some studies pointed out that mechanical resistance to fracture of endodontically treated teeth could be affected by the presence of posts and the risk of damage could increase [30,40,58]. In endodontically treated teeth, occlusal loads could be transferred intraradicularly by post restorations, increasing the occurrence of vertical root fractures. On the contrary, other authors noticed that fiber posts reduced the risk of root fractures [25]. Actual consensus in restorative dentistry indicates that decementation or failure of posts is preferable than fracture of residual tooth structure[40, 59,60]. In this study failures in glass fiber post restored teeth were restorable. The less residual tooth structure the more important the physical properties of post-and-core systems [61].

This study confirmed that the reconstructed tooth is subject to most stress in the cervical region under a functional load. Pierrisnard et al. [32] mentioned that the absence of a cervical ferrule was a negative factor giving rise to considerably higher stress levels. They also concluded that the cervical area of a root canal treated and restored teeth was the area most subject to stress under a simulated occlusal load.

Several studies have been performed to assess the mechanical resistance to fracture of post restored teeth [6-45]. Most studies have tried to identify the best technique and materials to be used to increase the strength of the toothrestoration complex [60,61]. The use of static forces permits to simplify the study realization [30,41] and requires universal testing machines easier to use and less expensive than fatigue and thermomechanical cycling test workstations [28,29,41,57]. In this study static loading was used to valididate the FEM results. Different loading jigs were described in the literature in shape and material [28-30,41]. In this study rounded tip with a diameter of 5 mm have been chosen to homogeneously apply loads [29-30]. Due to the large number of secondary variables involved [i.e. tooth type and condition, restorative procedures and materials], it is hard to compare experimental data extrapolated by different in vitro studies [41] but the results obtained from this fracture test were comparable with earlier reports [18,20].

5. Conclusion

FE analysis is a powerful tool in calculating stress distributions in complex structures. As stated earlier, the method provides results without variation. The validity of the study, however, depends on the extent to which the model approaches reality.

In functional loading, maximum equivalent stress mostly occurs at the vestibular side of the cement layer

Horizontal loading from the buccal aspect increased and vertical loads decreased the maximum stress.

Minimum stress values were obtained with the glass fiber post bonded with an adhesive resin cement with low elastic modulus

The stresses decreased with the post material in order of steel, zirconium, titanium, glass fiber with low modulus adhesive cement.

The stresses decreased in order of glass fiber, titanium, zirconium, steel with high modulus adhesive cement.

There was a significant difference in the stress distribution at dentin interfaces for the glass post restored tooth cemented with materials of different rigidity.

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