©Operative Dentistry, 2016, **41-5,** E149-E158

Fractographical Analysis and Biomechanical Considerations of a Tooth Restored With Intracanal Fiber Post: Report of the Fracture and Importance of the Fiber Arrangements

VF Wandscher • CD Bergoli • IF Limberger • TP Cenci • P Baldissara • LF Valandro

Clinical Relevance

When restoring anterior endodontically treated teeth, fiber posts with parallel fibers support tensile stresses, but they commonly fracture by shear stresses due to anterior occlusal oblique loads that generate bending of the restorative assembly.

SUMMARY

Objective: This article aims to present a fractographic analysis of an anterior tooth restored with a glass fiber post with parallel fiber arrangement, taking into account force vectors, finite element analysis, and scanning electron microscopy (SEM).

Methods: A patient presented at the Faculty of Dentistry (Federal University of Santa Maria, Brazil) with an endodontically treated tooth (ETT), a lateral incisor that had a restorable fracture. The treatment was performed, and the fractured piece was analyzed using stereomicroscopy, SEM, and finite element analysis.

Vinicius Felipe Wandscher, DDS, MSciD, PhD student, Graduate Program in Oral Science, Prosthodontics Unit, Faculty of Odontology, Federal University of Santa Maria, Santa Maria, RS, Brazil

Cesar Dalmolin Bergoli, DDS, MSciD, PhD, adjunct professor, Federal University of Pelotas, Restorative Dentistry (Prosthodontics), Pelotas, RS, Brazil

Inacio Fontoura Limberger, BEng, PhD, associate professor, Faculty of Mechanical Engineering, Federal University of Santa Maria, Santa Maria, RS, Brazil

Tatiana Pereira-Cenci, DDS, MSciD, PhD, adjunct professor, Restorative Dentistry (Prosthodontics), Federal University of Pelotas, Pelotas, RS, Brazil

Paolo Baldissara, DDS, researcher, Department of Biomedical and Neuromotor Sciences, Division of Prosthodontics and Maxillofacial Rehabilitation, *Alma mater Studiorum* University of Bologna, Bologna, Italy

*Luiz Felipe Valandro, PhD, DDS, MSciD, PhD, associate professor, head of MSciD/PhD Graduate Programs in Oral Science, Faculty of Odontology, Federal University of Santa Maria, Santa Maria, RS, Brazil

*Corresponding author: Rua Floriano Peixoto 1184, Santa Maria, Rio Grande do Sul 97015-372, Brazil; e-mail: lfvalandro@hotmail.com

DOI: 10.2341/15-262-S

Results: The absence of remaining coronal tooth structure might have been the main factor for the clinical failure. We observed different stresses actuating in an ETT restored with a fiber post as well as their relationship with the ultimate fracture. Tensile, compression, and shear stresses presented at different levels inside the restored tooth. Tensile and compressive stresses acted together and were at a maximum in the outer portions and a minimum in the inner portions. In contrast, shear stresses acted concomitantly with tensile and compressive stresses. Shear was higher in the inner portions (center of the post), and lower in the outer portions. This was confirmed by finite element analysis. The SEM analysis showed tensile and compression areas in the fiber post (exposed fibers=tensile areas=lingual surface; nonexposed fibers =compression areas=buccal surface) and shear areas inside the post (scallops and hackle lines). Stereomicroscopic analysis showed brown stains in the crown/root interface, indicating the presence of microleakage (tensile area=lingual surface).

Conclusion: We concluded that glass fiber posts with parallel fibers (0°), when restoring anterior teeth, present a greater fracture potential by shear stress because parallel fibers are not mechanically resistant to support oblique occlusal loads. Factors such as the presence of remaining coronal tooth structure and occlusal stability assist in the biomechanical equilibrium of stresses that act upon anterior teeth.

INTRODUCTION

The preservation of the remaining coronal structure has emerged as a crucial aspect for the clinical success of post-retained restorations and seems to be more important than the post choice.[1-8] Clinical trials have confirmed the strong scientific evidence that, irrespective of restorative technique of pulpless teeth, the preservation of at least one coronal wall and 2 mm of ferrule to post placement significantly reduces the clinical failure risk.[6,9,10]

Several available post systems have been proposed for the rehabilitation of endodontically treated teeth (ETT). It is known that cast posts and cores are associated with high rates of irreversible fractures[11,12] because they transfer more stress to the root dentin compared with fiber posts.[13-16] Fiber posts have an elastic modulus similar to that of dentin and are usually associated with repairable failures[17,18] because they more homogeneously distribute stress along the root and thereby prevent root fracture.[13,19-21]

Given that the use of fiber posts has increased, it is important to assess how the magnitude and direction of functional loads play a major role in the concentration of stress within teeth restored with posts.[22,23] Horizontal loads lead to a significantly higher concentration of stress within dentin than loads parallel to the long axis of the tooth.[24-28] Because the loads are applied at different levels along the dental arch, anterior teeth are most likely to be subjected to more horizontally directed loads due to their inclination in relation to posterior teeth.[23,29] For example, a force applied at an angle of 90° to the anterior teeth causes the appearance of tensile and compressive stresses,[30] which can cause damage to teeth restored with posts because these teeth have weaker supporting structures.

In addition, resolution of the load applied at 45° into force vectors using fractographical analysis facilitated the modeling of the specific features of stress (tensile, compression, and shear) found in an anterior ETT fractured after mechanical cycling.[31] These data are corroborated by the results of another study that found that the elastic modulus of a post, with regard to concentration, magnitude, and direction of dentinal stress, was dependent on the direction of the applied load.[14] When examining models of posts with a high modulus, it was found that horizontal loads led to more stress on the apical area of the root; such loads suggested a vertical root fracture. On the other hand, when low-modulus posts were modeled, forces at 45° and 90° caused more stress on the cervical area, with a direction that suggests debonding of the post.

The direction of the applied force and the fiber arrangement of fiber-reinforced polymeric materials (FRP) directly influence their mechanical properties.[32] Glass fiber posts (classified as a FRP) generally present longitudinal fibers (parallel fibers, 0°) distributed inside the polymeric matrix, so they can support high tensile stress when the forces are applied along their central axis.[33] However, when oblique forces (45°) are applied (anterior teeth), shear stresses are induced inside the polymer, leading to fracture by lower loads than when only tensile stresses are generated.[32-34] Recently, *in vitro* studies showed that shear stresses can be as harmful as tensile and compression stresses when oblique forces are applied in ETT restored with fiber

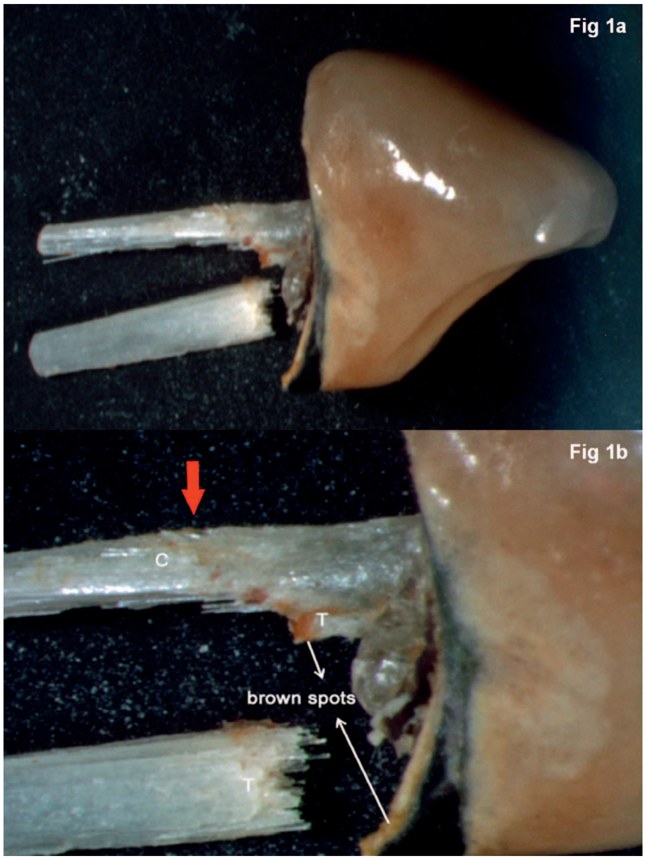

Figure 1. *Representative images of the fractured assembly. a: the fiber post fractured wherein one piece was broken (area submitted to tensile stresses) and the other was attached to the core/crown part (area submitted to compressive stresses). b: tensile (T) and compressive (C) regions. In the buccal region there is a "kneading" of the fiber post (red arrow: superficial fibers exposed and mild bulge in the outer surface).*

posts[31,35] or when only glass fiber posts were submitted to static[33,34] and fatigue loads.[33]

Thus, our aim was to perform a fractographical analysis of an endodontically treated upper lateral incisor restored with a glass fiber post and a metal-ceramic crown that fractured after three years of clinical service and compare that with *in vitro* findings available in the literature. We sought to assess the forces exerted on the fractured tooth with both a finite element and a scanning electron microscopy (SEM) analysis as well as to validate the *in vitro* findings.

METHODS

Case Description

A 49-year-old man presented at the Division of Prosthodontics with a fracture in the upper left lateral incisor, incurred while eating. Previously, on September 28, 2010, the patient had been referred to the Division of Prosthodontics of the Faculty of Dentistry with a large coronal fracture in the tooth, which had already been endodontically treated. A detailed anamnesis was performed. The patient had good general and dental health but was missing the maxillary right second premolar, first molar and second molar, as well as the maxillary left first premolar, second premolar, and first molar. The initial focus of the treatment was on the rehabilitation of the fractured tooth, followed by replacement of the other lost teeth. After clinical and radiographic examinations, we proposed restoration of the lateral incisor with an intraradicular post and metal-ceramic crown as well as a removable partial denture (RPD) for the maxillary posterior segments. The fractured lateral incisor presented two proximal contacts, was a sound tooth antagonist with periodontal support, had a mobility grade of 0, and had a remaining root length of 16 mm.

Rehabilitation consisted of the cementation of a glass fiber post (White Post DC, FGM, Joinville, Brazil) using a self-adhesive cement (RelyX U100; 3M ESPE, St Paul, MN, USA). It was cemented at a 10-mm length, with a 6-mm coronal length and 1.6-mm coronal diameter.

On January 3, 2013, the patient sought assistance again due to a post-meal fracture in the previously rehabilitated lateral incisor. The patient brought the fractured restoration, and during examination, the following was observed: 1) the metal-ceramic crown, composite core, and fiber post were still luted together; (2) the fiber post had fractured into two pieces, approximately at cervical level, as described in the literature;[14] 3) resin cement had adhered to the dentin, indicating an adhesive cement-post failure; and 4) according to the patient, an RPD had not been affixed in the posterior maxilla due to financial reasons.

We observed the root integrity and proposed cementing a new post and creating a new restoration. We explained to the patient the importance of an RPD to stabilize the occlusion, and the RPD was then manufactured to avoid overloading of the anterior segment of the maxilla. The parts of the fractured restoration were analyzed using a stereomicroscope (Discovery V20, Carl Zeiss, Göttingen, Germany; Figure 1) and an SEM (Jeol JSM 5400, Jeol Ltd, Tachikawa, Japan; Figure 2).

Finite Element Analysis

A two-dimensional model of a lateral incisor was created using the software CAD Rhinoceros (version

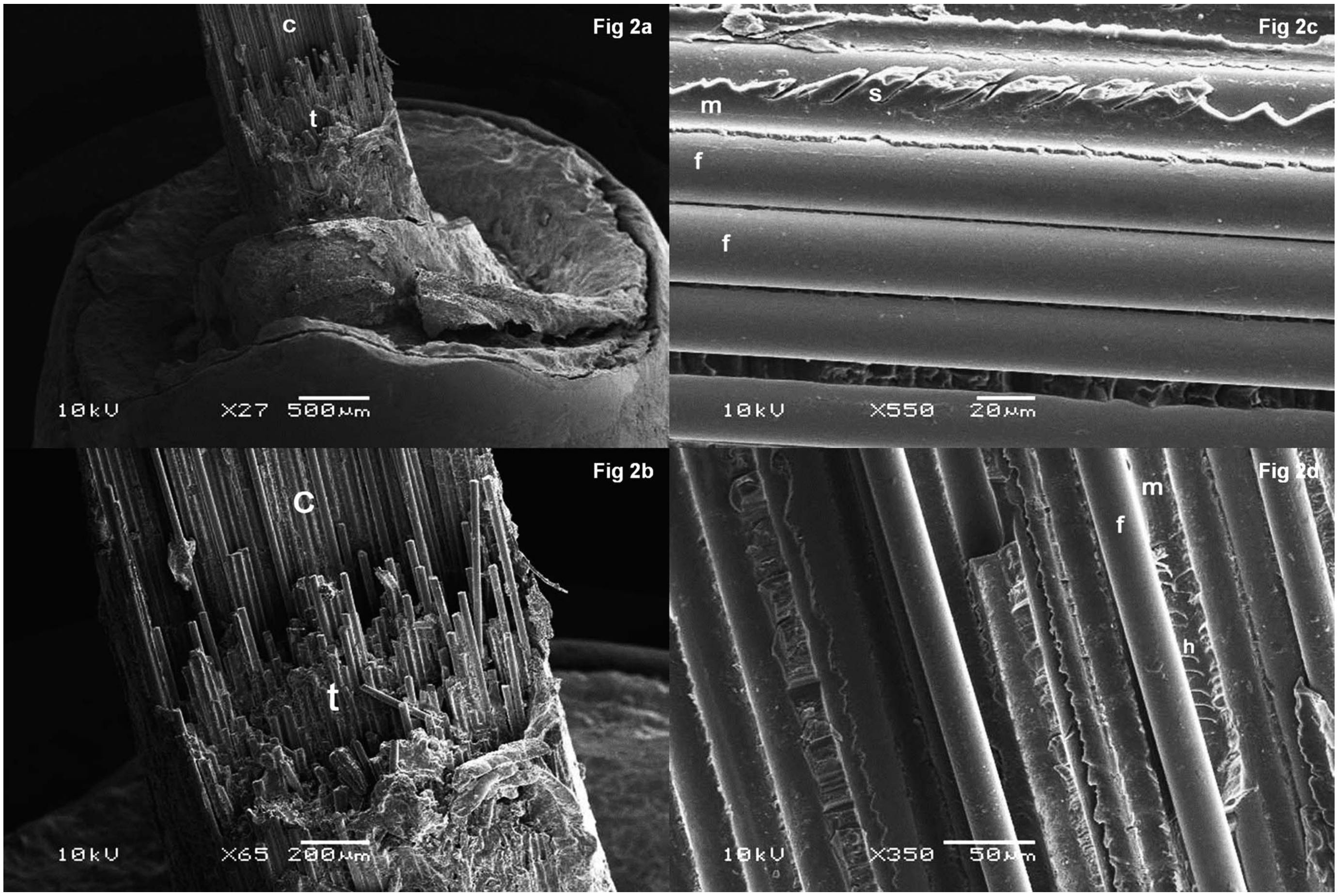

Figure 2. *Scanning electron microscope images. a and b: lingual portion; t = fiber post region submitted to the tensile stresses (specific features: glass fibers exposed without matrix); c = compression.[31] c and d: analysis of parallel surface fractured (specific features: f = glass fibers, m = epoxy matrix exposed showing the concavity, adhesive failure between fiber/matrix, s = scallops and h = hackle lines,[32,33] failures characteristic of shear stress).*

4.0SR8, McNeel North America, Seattle, WA, USA) to simulate the bone; the periodontal ligament (0.3 mm); the root (length: 15 mm; width: 7 mm); the gutta-percha; the resin cement thickness between the fiber post and root dentin (100 µm); the fiber post; a resin composite core (height: 7 mm; width: 5.5 mm); the cement thickness between the core and the metal-ceramic crown (100 µm); and a metal-ceramic crown (height: 9 mm; infrastructure thickness: 0.5 mm; ceramic width: 0.7 mm). A chamfer of 1.2 mm was designed at the vestibular and lingual portions. The fiber post was modeled with 10 mm inside the root canal and 5 mm at the coronal portion.

After modeling, the geometry was imported into an STP format to Ansys software (Ansys 13.0, Houston, TX, USA) for boundary conditions and numerical simulation. Tetrahedron elements were used, generating a total of 27,264 elements and 29,549 nodes. After the convergence test, the mean size of the elements was 0.15 mm, with the exception of the fiber post and the resin cement, which presented elements of 0.05 mm. The interfaces were considered bonded, and the base and lateral faces of the bone were considered fixed in the x, y, and z directions. A force of 70 N (an intermediate value used in the study of Wandscher and others)[31] was applied at 45° to an area of 1 mm^2 situated 2 mm below the incisal edge of the crown. The fiber posts were considered orthotropic, whereas other materials were considered isotropic (Table 1).[36-43] All materials were considered homogeneous and linear elastic. The maximum principal stress, minimum principal stress, and shear stress were evaluated using the model.

RESULTS

Analysis of the Prosthetic Fragment

The images derived from the stereomicroscope showed that the failure occurred in the fulcrum

Table 1: *Materials, Elastic Modulus, Poison Values, and References Consulted to Obtain the Values*

Material	Elastic Modulus (GPa)	Poison	Reference
Dentin	18.6	0.31	Peyton and others[36]
Composite resin	15	0.24	Versluis and others[37]
Glass fiber post	40 11	0.26 0.07 0.32	Pegoretti and others[38]
Resin cement	2.6	0.33	Pegoretti and others[38]
Gutta-percha	0.14	0.45	Friedman and others[39]
Periodontal ligament	0.0000689	0.45	Yettram and others[40]
Cortical bone	13.7	0.3	Borchers and others[41]
Porcelain	65	0.24	Eraslan and others[42]
Framework of nickel-chromium	200	0.3	Williams and others[43]

region, below the tooth cervical level (approximately 3 mm), in which one post piece was broken and the other was attached to the restorative core/crown (Figure 1a,b). It is possible to observe palatine staining (brown spots) on the marginal cement and on the fiber post (Figure 1b) due to marginal leakage. The SEM images showed the fractured parts, consequences of the tensile and compression stresses (Figure 2a,b) and shear stress (scallops: Figure 2c; hackle lines: Figure 2d).

Figure 3 shows the bending moments and the fulcrum lines. The periodontal ligament permitted tooth movement and the 45° load (F) promoted tooth bending, forming a fulcrum line at the bone crest level (fulcrum 1: red line). In addition, at the cervical level another fulcrum line was formed by a 45° load and the cervical surface of the root (fulcrum 2: green line). The bending moment (M) was measured by the applied force (F) and the distance between the load application point and the fulcrum line (d).[44] Because the moment is directly proportional to the distance, the higher the distance, the higher the bending moment. The distance between the loading point and fulcrum 1 is higher than the distance between the loading point and fulcrum 2, so moment 1 (M1) is higher than moment 2 (M2). Thus, the consequences of M1 on the post were higher, leading to a fracture at that point (Figure 1b).

Figure 4 presents the stresses that acted on the restored tooth, the graphic of tension, and the formulas. By means of the parallelogram law,[44,45] the 45° force has been mathematically decomposed into a cartesian axis in force vectors to obtain the horizontal (F_x) and vertical (F_y) components of F (Figure 4a). F_x produces compressive loading (C) uniformly distributed in the cross-section as shown in the graphic of tension (Figure 4b). F_y produces transverse loading bending on the dental structure, generating normal tensile stresses (T) on the lingual surface and normal compression stresses (C) on the buccal surface as presented in the graphic of tension. These stresses tend to be zero or a minimum in the center of the dental element (N_L) and a maximum in the outer portions (Figure 4c). The sum of B and C results in the A graphic of tension, where it is possible to observe displacement of the neutral line to the lingual surface because there is more compressive stress acting in the structure. F_y also produces shear stress in parallel planes to the longitudinal axis of the structure due to the transverse loading. This stress is at a minimum at the outer portions and a maximum at the center, as noted in the graphic of tension (Figure 4d).[31,33,44,45]

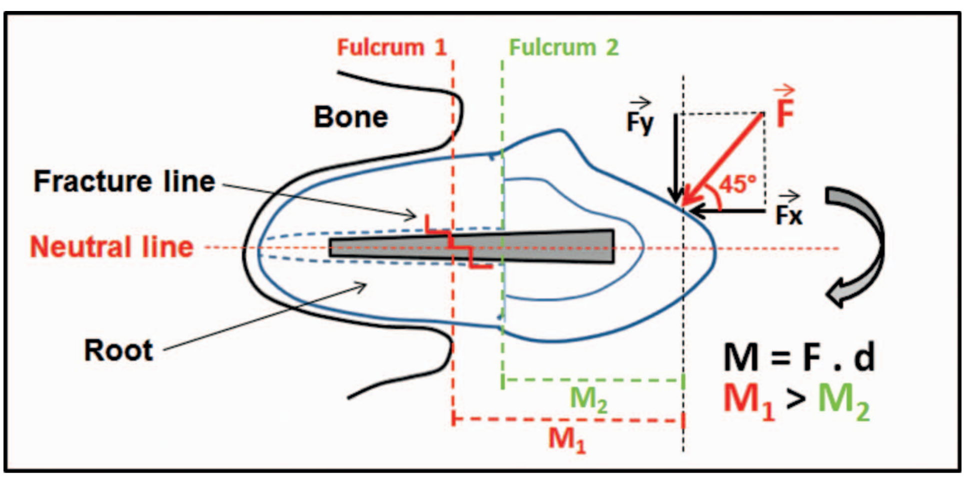

Figure 3. *Schematic representation of the bending moments, which act on the post. F red: 45° load; Fy = vertical component of 45° load; Fx = horizontal component of 45° load; M = bending moment; black F = applied force; d = distance between the load application point and the fulcrum line; M_1 = bending moment at fulcrum line 1; M_2 = bending moment at fulcrum line 2.*

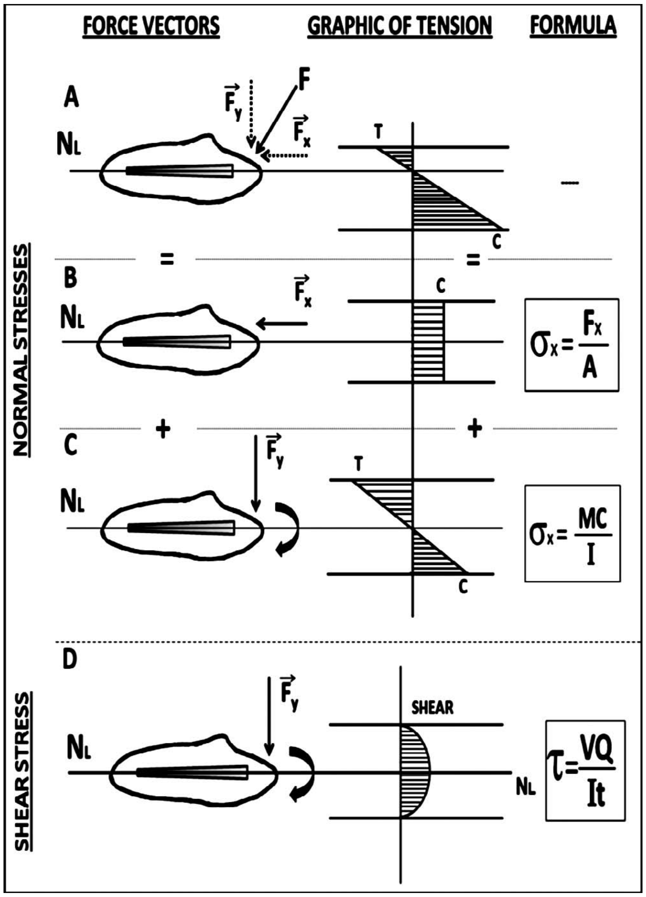

Figure 4. *Graphic representation of the normal stresses (stresses that act in the same sense as the neutral line –* N_L*) and shear stress on the dental structure.* ***A:*** *mathematically decomposed into a Cartesian axis in force vectors of 45° Force (F); Fx (horizontal component of F) and Fy (vertical component of F); T = tensile stress; C = compression stress.* ***B:*** *effect of horizontal component of F on the tooth; Graphic of tension of Fx;* $\sigma_x = F / A$*, where* σ_x *is the normal stress in the X direction and A is area.* ***C:*** *effect of vertical component of F on the tooth (tensile and compression); Graphic of tension of Fy; T = tensile stress; C = compression stress;* $\sigma_x = MC / I$*, where M = bending moment, C = distance from the neutral line to the most requested fiber, and I = moment of inertia of area.* ***D:*** *effect of vertical component of F on the tooth (shear);* $\tau = VQ / It$*, where* τ *= shear stress, V = force (Fy), Q = static moment of area, I = moment of inertia of area, and t = thickness of the flat section area.*[33,44,45]

Finite Element Analysis

Finite element analysis (Figure 5) presents numeric stress values of compression, tensile, and shear on the post after 45° load application. Compression and tensile stresses are considered normal tensions because they act in the long axis of the tooth. These stresses are at a maximum in the outer portions of the post. It is possible to observe that the higher value of compression stress is on the buccal region of the post (point C—Figure 5a) and the higher value of tensile stress is on the lingual region of the post (point A—Figure 5b). In relation to shear stress, the values were maximum in the center and minimum in the outer portions (points B and B′—Figure 5c).

It is important to note that features found in the fractographic analysis coincide with biomechanical and finite element analysis (scallops and hackle lines: maximum shear zones; glass fibers exposed without matrix: maximum tensile zones; kneading: maximum compression zones).

DISCUSSION

Clinical studies[1,2,6,7] and literature reviews[3,4,5,8] have shown that the greater the remaining coronal tooth structure, the greater the survival of posts. In addition, long-term follow-up investigations assessing several tooth types have demonstrated that the survival of teeth with substantial tooth tissue is unaffected by the use of a post.[7,46-48] This means the presence of remaining coronal structure rather than the type of post is the most important clinical condition for success of ETT. *In vitro* studies have stated that teeth with at least 2 mm of remaining coronal structure provide higher fracture resistance,[9,49,50] and greater ferrule promotes a more homogeneous stress distribution in ETT and a lower probability of clinical failure.[50-52]

Before discussing the biomechanical issues of the current forensic investigation, it is important to emphasize that the patient in this case report had no remaining coronal tooth structure, which might have caused (or elevated the risk of) the clinical failure. The factors discussed next should be considered secondary to remaining coronal tissue when analyzing ETT restored with posts.

Anterior teeth experience different load levels, principally oblique loads that lead to bending of the restored tooth.[14,23,29] Such loads result in extremely harmful stresses (tensile/compression[30,31,33-35]and shear stresses[31,33,34,35]) on an ETT restored with a post.

It is likely that the fracture of the lateral incisor can be attributed to an association of reasons. According to Figure 1a and b, the fracture occurred in the fulcrum zone 3 mm below the cervical level. As seen in Figure 3, two fulcrum lines formed on the post: one at the bone crest level and the other at the cervical level. The bending moment is the reaction induced in a structure when an external force, or moment, is applied to the element, causing bending.[44] The current fracture occurred at the farther point of load application, on M1 (where the bending effects are greatest).

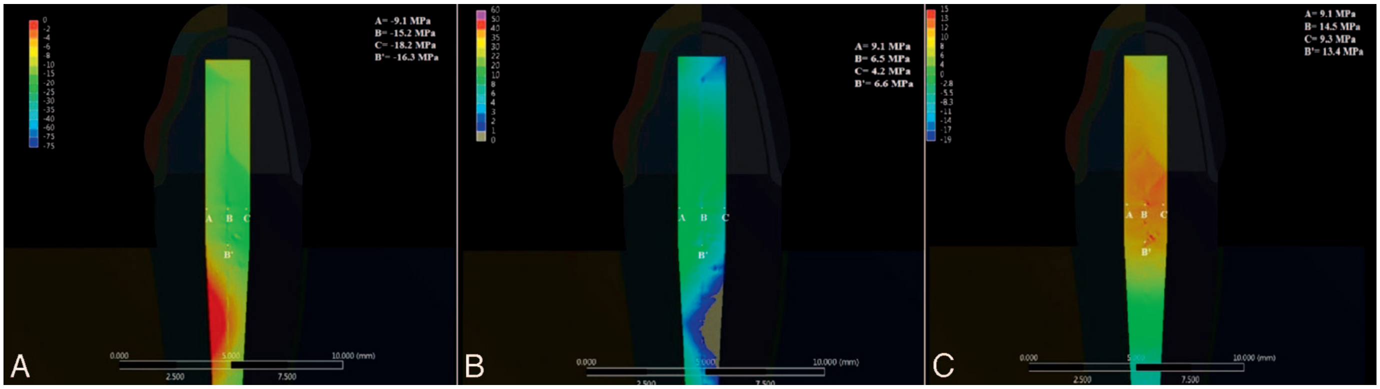

Figure 5. *Representative images of the finite element analysis. In A: minimum principal stress (compressive stress). There is a higher compression stress value on the buccal surface (point C) of the post. B: maximum principal stress (tensile stress). There is a higher tensile stress value on the lingual surface (point A) of the post. C: maximum shear stress (shear stress). There is a higher shear stress value on the center of the post (point B).*

Second, failure analysis made it possible to observe areas characterized by tensile, compression, and shear forces. Anterior teeth are positioned in the dental arch at an approximate angle of 45°. Any oblique load exerted under these teeth leads to bending of the dental structure and results in the onset of tensile, compression, and shear stresses.[31,33,35] A classic study described tensile and compressive stresses in a tooth undergoing bending.[30] More recently, other *in vitro* studies have analyzed these concepts in the failure analysis of both fiber posts and ETT restored with posts;[31,33,35] these observed that shear stress was present and may be as detrimental to restorative structures as tensile and compressive stresses.

During bending, tensile and compression stresses operate on the teeth, with the stresses at a maximum in the outer portions and a minimum in the center of the restoration assembly. The opposite occurs with shear stress; that is, the stress is at a maximum in the center and a minimum in the outer portions (Figure 4d).[31,33-35,44,45] The effects of tensile and compression stresses are observed in Figure 2 under the assembly crown/core/post. Primarily, due to tensile stress,[53] an adhesive failure between tooth and post buildup (subcritical tensile failure of buildup/dentin interface[54]) promoted a marginal leakage, first at the margin (brown staining spots), and then penetrating into the restoration (brown spots on fiber post, Figure 1b). This adhesive failure indicates the presence of a crack in the palatal region[55] as a consequence of the debonding of the core/crown due to the tensile stress that promoted bending of the intraradicular glass fiber post and the catastrophic failure of the crown.

Moreover, tensile stresses may be observed in the fiber post fracture. The lost part indicates the surface exposed to tensile stress (lingual portion). It is characterized by the presence of lost fibers without a matrix in both fractured parts (Figure 2a,b), as opposed to the surface exposed to compressive stress (Figures 1b and 2a,b). The compressive area is characterized by a "kneading" in which fiber bending occurs with compression of the matrix. These features were also found in an *in vitro* study that evaluated mechanical cycling and fracture load of weakened roots restored with posts.[31] Finite element analyses showed the values of force in the areas of tensile and compression stresses inside the post (Figure 5). These values presented low magnitudes, when compared with the force applied on the palatal region, and could be explained by the dissipation of the stresses through the model.

Shear stress also negatively affected the restored ETT (Figure 4d), and it was concentrated strongly in both the center of the post and in the cement layer (considered a fragile area and subject to defects). In Figure 5c, it is possible to observe the virtual values of shear stress (higher in the center and lower in the outer portions) in the horizontal and vertical planes of fiber posts, which explains the failure behavior of this system.[31,33,35,44,45] This explains why the failure in the central region of the post was classified as intralaminar mode II in-plane shear inside the post,[32-34] and it presents as hackles and scallops where they intersect adjoining areas of fiber-to-matrix separation (Figure 2c,d). Another explanation for the fiber post failure could be related to an initial adhesive failure between fiber post and root dentin, which could lead to concentrated stresses at the fiber post and the root dentin, as explained by Santos and others,[56] and could explain why the fiber post failed under a low magnitude of force. Unfortunately, it was not possible to model a nonbonding condition (nonlinear). Recent *in vitro* studies have found the same fracture mode by shear stress in fiber posts subjected to bending,[33,34] as well as fracture resistance after mechanical cycling of roots restored with fiber posts.[35] These *in vitro* results support the finding of the current forensic investigation.

Another important topic is the fiber post behavior when a load is applied to the restorative structure. A fiber post with longitudinal parallel fibers (0°) presents high resistance if force is applied to the longitudinal axis, but when oblique forces are applied, the post's response is different. The fiber arrangement inside the post directly affects its mechanical properties.[32-34] Fiber posts with parallel fibers (as in the current forensic investigation) have limited ability to support an oblique load (ie, 45° inclination) and may fracture with lower loads due to shear stress compared with tensile loads.[33] An alternative to this problem could be the development of fiber posts with different fiber arrangements (other fiber alignment angles) that are able to support loads in different directions. This finding supports the results presented by previous *in vitro* studies that used fiber posts with parallel fiber arrangements (0°).[33,34]

It is difficult to predict exactly where the fracture initiated; however, it is likely that initially there was a failure by shear stress inside the post due to the limited capacity to support bending stresses, leading to an adhesive failure in the lingual portion of the core (indicated by brown spots on Figure 1b).

The criteria for an acceptable dental occlusion involve the presence of axial bilateral posterior contacts and either absence of contacts or smooth contacts in the anterior region.[57] In this clinical situation, the patient had lost posterior dental occlusion, which overloaded the restoration and intensified the consequences of the tension, compression, and shear loads in the restored lateral incisor.

Factors such as the quantity of the remaining dental structure, the position of the tooth in the arch, the absence of posterior support, the selection and adequate application of the restorative strategy, the type of antagonist, and the presence of RPDs are important issues to be evaluated. The negligence of these factors may result in a greater effect of the bending loads (tensile, compression, and shear) on ETT anterior teeth. For ETT restored with fiber posts, the remaining coronal tooth structure and the resulting ferrule are very important to increase the survival of the restoration.

In conclusion, it is important to emphasize that two factors were critical to the fracture of the restored lateral incisor: the significant loss of remaining coronal tooth structure and the lack of posterior occlusal support. If the coronal structure was larger and there were occlusal bilateral contacts, the effects of the stresses would be minimized and the biomechanical stability of the restorative assembly would probably be assured.

CONCLUSION

Given the limitations of this clinical report, some considerations can be drawn.

1. The fracture did not occur by one single factor but due to the association of several factors.
2. When restoring an ETT, the preservation of the remaining coronal tooth structure is a must.
3. The theories formulated in *in vitro* studies appear to be correct: Anterior ETT restored with posts suffer tensile, compressive, and shear stresses across the buccolingual depth at the cervical level. The failure described in the clinical situation of the current study is in accordance with other *in vitro* studies that described favorable or reparable failures in ETT restored with fiber posts.
4. The development of fiber posts with different fiber arrangements capable of withstanding both axial and oblique forces may be one possible solution to assist in anterior ETT rehabilitation.
5. In teeth restored with posts and cores, knowledge of the direction of the forces operating is strongly advisable, especially considering that these forces vary according to the position of the restored teeth in the dental arch (anterior or posterior teeth).

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the Federal University of Santa Maria, Brazil.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 18 February 2016)

REFERENCES

1. Creugers NH, Mentink AG, Fokkinga WA, & Kreulen CM (2005) 5-year follow-up of a prospective clinical study on various types of core restorations *International Journal of Prosthodontics* **18(1)** 34-39.

2. Naumann M, Blankenstein F, Kiessling S, & Dietrich T (2005) Risk factors for failure of glass fiber-reinforced composite post restorations: A prospective observational clinical study *European Journal of Oral Sciences* **113(6)** 519-524.
3. Dietschi D, Duc O, Krejci I, & Sadan A (2008) Biomechanical considerations for the restoration of endodontically treated teeth: A systematic review of the literature, part II (Evaluation of fatigue behavior, interfaces, and *in vivo* studies) *Quintessence International* **39(2)** 117-129.
4. Cagidiaco MC, Goracci C, Garcia-Godoy F, & Ferrari M (2008) Clinical studies of fiber posts: A literature review *International Journal of Prosthodontics* **21(4)** 328-336.
5. Al-Omiri MK, Mahmoud AA, Rayyan MR, & Abu-Hammad O (2010) Fracture resistance of teeth restored with post-retained restorations: An overview *Journal of Endodontics* **36(9)** 1439-1449.
6. Ferrari M, Vichi A, Fadda GM, Cagidiaco MC, Tay FR, Breschi L, Polimeni A, & Goracci C (2012) A randomized controlled trial of endodontically treated and restored premolars *Journal of Dental Research* **91(7)** 72S-78S.
7. Naumann M, Koelpin M, Beuer F, & Meyer-Lueckel H (2012) 10-year survival evaluation for glass-fiber-supported postendodontic restoration: A prospective observational clinical study *Journal of Endodontics* **38(4)** 432-435.
8. Soares CJ, Valdivia AD, da Silva GR, Santana FR, & Menezes Mde S (2012) Longitudinal clinical evaluation of post systems: A literature review *Brazilian Dental Journal* **23(2)** 135-140.
9. Naumann M, Preuss A, & Frankenberger R (2007) Reinforcement effect of adhesively luted fiber reinforced composite versus titanium posts *Dental Materials* **23(2)** 138-144.
10. Bitter K, Noetzel J, Stamm O, Vaudt J, Meyer-Lueckel H, Neumann K, & Kielbassa AM (2009) Randomized clinical trial comparing the effects of post placement on failure rate of postendodontic restorations: Preliminary results of a mean period of 32 months *Journal of Endodontics* **35(11)** 1477-1482.
11. Ferrari M, Vichi A, & García-Godoy F (2000) Clinical evaluation of fiber-reinforced epoxy resin posts and cast post and cores *American Journal of Dentistry* **13(Special Number)** 15B-18B.
12. Piovesan EM, Demarco FF, Cenci MS, & Pereira-Cenci T (2007) Survival rates of endodontically treated teeth restored with fiber-reinforced custom posts and cores: A 97-month study *International Journal of Prosthodontics* **20(6)** 633-639.
13. Coelho CS, Biffi JC, Silva GR, Abrahão A, Campos RE, & Soares CJ (2009) Finite element analysis of weakened roots restored with composite resin and posts *Dental Materials Journal* **28(6)** 671-678.
14. Meira JB, Espósito CO, Quitero MF, Poiate IA, Pfeifer CS, Tanaka CB, & Ballester RY (2009) Elastic modulus of posts and the risk of root fracture *Dental Traumatology* **25(4)** 394-398.
15. Yamamoto M (2009) Photoelastic stress analysis of different post and core restoration methods *Dental Materials Journal* **28(2)** 204-211.
16. Asvanund P, & Morgano SM (2011) Photoelastic stress analysis of different prefabricated post-and-core materials *Dental Materials Journal* **30(5)** 684-690.
17. Fokkinga WA, Le Bell AM, Kreulen CM, Lassila LV, Vallittu PK, & Creugers NH (2005) *Ex vivo* fracture resistance of direct resin composite complete crowns with and without posts on maxillary premolars *International Endodontic Journal* **38(4)** 230-237.
18. Stricker EJ, & Göhring TN (2006) Influence of different posts and cores on marginal adaptation, fracture resistance, and fracture mode of composite resin crowns on human mandibular premolars. An *in vitro* study *Journal of Dentistry* **34(5)** 326-335.
19. Lanza A, Aversa R, Rengo S, Apicella D, & Apicella A (2005) 3D FEA of cemented steel, glass and carbon posts in a maxillary incisor *Dental Materials* **21(8)** 709-715.
20. Spazzin AO, Galafassi D, de Meira-Júnior AD, Braz R, & Garbin CA (2009) Influence of post and resin cement on stress distribution of maxillary central incisors restored with direct resin composite *Operative Dentistry* **34(2)** 223-229.
21. Mezzomo LA, Corso L, Marczak RJ, & Rivaldo EG (2011) Three-dimensional FEA of effects of two dowel-and-core approaches and effects of canal flaring on stress distribution in endodontically treated teeth *Journal of Prosthodontics* **20(2)** 120-129.
22. Bergman B, Lundquist P, Sjogren U, & Sundquist G (1989) Restorative and endodontic results after treatment with cast posts and cores *Journal of Prosthetic Dentistry* **61(1)** 10-15.
23. Mehta SB, & Millar BJ (2008) A comparison of the survival of fibre posts cemented with two different composite resin systems *British Dental Journal* **205(11)** E23.
24. Yang HS, Lang LA, Molina A, & Felton DA (2001) The effects of dowel design and load direction on dowel-and-core restorations. *Journal of Prosthetic Dentistry* **85(6)** 558-567.
25. Loney RW, Moulding MB, & Ritsco RG (1995) The effect of load angulation on fracture resistance of teeth restored with cast posts and cores and crowns *International Journal of Prosthodontics* **8(3)** 247-251.
26. Joshi S, Mukherjee A, Kheur M, & Mheta A (2001) Mechanical performance of endodontically treated teeth *Finite Elements in Analysis and Design* **37(8)** 587-601.
27. Yaman SD, Karacaer O, & Sahin M (2004) Stress distribution of post-core applications in maxillary central incisors *Journal of Biomaterials Applications* **18(3)**163-177.
28. Abu-Hammad O, & Dar-Odeh N (2004) Factors affecting the stress picture in a molar tooth restored with an endodontic post retained filling. Part 1: The stress picture with the system under various loading conditions *Cairo Dental Journal* **20** 121-124.
29. Fernandes A, & Dessai G (2001) Factors affecting the fracture resistance of post-core reconstructed teeth: A review *International Journal of Prosthodontics* **14(4)** 355-363.

30. Assif D, & Gorfil C (1994) Biomechanical considerations in restoring endodontically treated teeth *Journal of Prosthetic Dentistry* **71(6)** 565-567.

31. Wandscher VF, Bergoli CD, Limberger IF, Ardenghi TM, & Valandro LF (2014) Preliminary results of the survival and fracture load of roots restored with intracanal posts: Weakened vs nonweakened roots *Operative Dentistry* **39(5)** 541-555.

32. Shipley RJ, & Becker WT (2002) Failure analysis continuous fiber reinforced composites In: Smith TW, Grove RA (eds), *ASM Handbook: Failure Analysis and Prevention* **10th edition volume 11** ASM International, Russell Township, OH, 731-743.

33. Wandscher VF, Bergoli CD, de Oliveira AF, Kaizer OB, Souto Borges AL, Limberguer Ida F, & Valandro LF (2015) Fatigue surviving, fracture resistance, shear stress and finite element analysis of glass fiber posts with different diameters *Journal of the Mechanical Behavior of Biomedical Materials* **43(March)** 69-77.

34. Pereira GK, Lançanova M, Wandscher VF, Kaizer OB, Limberger I, Özcan M, & Valandro LF (2015) Fiber-matrix integrity, micromorphology and flexural strength of glass fiber posts: Evaluation of the impact of rotary instruments *Journal of the Mechanical Behavior of Biomedical Materials* **48(August)** 192-199.

35. Marchionatti AM, Wandscher VF, Broch J, Bergoli CD, Maier J, Valandro LF, & Kaizer OB (2014) Influence of periodontal ligament simulation on bond strength and fracture resistance of roots restored with fiber posts *Journal of Applied Oral Science* **22(5)** 450-458.

36. Peyton FA, Mahler DB, & Hershenov B (1952) Physical properties of dentin *Journal of Dental Research* **31(3)** 366-370.

37. Versluis A, Tantbirojn D, & Douglas WH (1998) Do dental composites always shrink toward the light? *Journal of Dental Research* **77(6)** 1435-1445.

38. Pegoretti A, Fambri L, Zappini G, & Bianchetti M (2002) Finite element analysis of a glass fibre reinforced composite endodontic post *Biomaterials* **23(13)** 2667-2682.

39. Friedman CM, Sandrik JL, Heuer MA, & Rapp GW (1975) Composition and mechanical properties of gutta-percha endodontic points *Journal of Dental Research* **54(5)** 921-925.

40. Yettram AL, Wright KW, & Houston WJ (1977) Centre of rotation of a maxillary central incisor under orthodontic loading *British Journal of Orthodontics* **4(1)** 23-27.

41. Borchers L, & Reichart P (1983) Three-dimensional stress distribution around a dental implant at different stages of interface development *Journal of Dental Research* **62(2)** 155-159.

42. Eraslan O, Aykent F, Yücel MT, & Akman S (2009) The finite element analysis of the effect of ferrule height on stress distribution at post-and-core-restored all-ceramic anterior crowns *Clinical Oral Investigations* **13(2)** 223-227.

43. Williams KR, Edmundson JT, & Rees JS (1987) Finite element stress analysis of restored teeth *Dental Materials* **3(4)** 200-206.

44. Beer FP, & Johnston RJr (1994) *Vector Mechanics for Engineers Statics* **5th edition** Makron Books do Brasil, São Paulo, Brazil.

45. Hibbeler RC (2006) *Mechanics of Materials* **5th edition** Pearson Prentice Hall, São Paulo, SP, Brazil.

46. Aurelio IL, Fraga S, Rippe MP, & Valandro LF (2015) Are posts necessary for the restoration of root filled teeth with limited tissue loss? A structured review of laboratory and clinical studies *International Endodontic Journal* online September 1, 2015 **doi: 10.1111/iej.12538**.

47. Fokkinga WA, Kreulen CM, Bronkhorst EM, & Creugers NH (2007) Up to 17-year controlled clinical study on post-and-cores and covering crowns *Journal of Dentistry* **35(10)** 778-786.

48. Zicari F, Van Meerbeek B, Scotti R, & Naert I (2013) Effect of ferrule and post placement on fracture resistance of endodontically treated teeth after fatigue loading *Journal of Dentistry* **41(3)** 207-215.

49. Pereira JR1, Valle AL, Shiratori FK, Ghizoni JS, & Melo MP (2009) Influence of intraradicular post and crown ferrule on the fracture strength of endodontically treated teeth *Brazilian Dental Journal* **20(4)** 297-302.

50. Zhang YY, Peng MD, Wang YN, & Li Q (2015) The effects of ferrule configuration on the anti-fracture ability of fiber post-restored teeth *Journal of Dentistry* **43(1)** 117-125.

51. Dejak B, & Młotkowski A (2013) The influence of ferrule effect and length of cast and FRC posts on the stresses in anterior teeth *Dental Materials* **29(9)** e227-e237.

52. Juloski J, Apicella D, & Ferrari M (2014) The effect of ferrule height on stress distribution within a tooth restored with fibre posts and ceramic crown: A finite element analysis *Dental Materials* **30(12)** 1304-1315.

53. Mattos CM, Las Casas EB, Dutra IG, Sousa HA, & Guerra SM (2012) Numerical analysis of the biomechanical behaviour of a weakened root after adhesive reconstruction and post-core rehabilitation *Journal of Dentistry* **40(5)** 423-432.

54. Libman WJ, & Nicholls JI (1995) Load fatigue of teeth restored with post and core and complete crowns *International Journal of Prosthodontics* **8(2)** 155-161.

55. Baldissara P, Di Grazia V, Palano A, & Ciocca L (2006) Fatigue resistance of restored endodontically treated teeth: A multiparametric analysis *International Journal of Prosthodontics* **19(1)** 25-27.

56. Santos AF, Meira JCB, Tanaka CB, Xavier TA, Ballester RY, Lima RG, Pfeifer CS, & Versluis A (2010). Can fiber posts increase root stresses and reduce fracture? *Journal of Dental Research* **89(6)** 587-591.

57. Okeson JP (2012) *Management of Temporomandibular Disorders and Occlusion* **7th edition** Elsevier, St Louis, MO, 468.