UNIVERSIDADE ESTADUAL DE CAMPINAS
FACULDADE DE ODONTOLOGIA DE PIRACICABA

Ricardo Armini Caldas

A falha de adesão deve ser simulada para análises de tensões em restaurações intracanais?

Should adhesive debonding be simulated for intra-radicular post stress analyses?

Piracicaba
2018

Ricardo Armini Caldas

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Tese apresentada à Faculdade de Odontologia de Piracicaba da Universidade Estadual de Campinas como parte dos requisitos para obtenção do título de Doutor em Clínica Odontológica na área de Prótese Dental.

Thesis presented to the Piracicaba Dental School of the University of Campinas in partial fulfillment of the requirements for the degree of Doctor in Dental Clinics, in Prosthodontics area.

Orientador: Valentim Adelino Ricardo Barão

Este exemplar corresponde à versão final da tese defendida pelo aluno Ricardo Armini Caldas e orientada pelo Prof. Dr. Valentim Adelino Ricardo Barão.

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A Ata da defesa com as respectivas assinaturas dos membros encontra-se no processo de vida acadêmica do aluno.

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EPÍGRAFE

"All models are wrong. Some models are useful"

(George E. P. Box)

RESUMO

As análises computacionais de tensões em restaurações intracanais por vezes apresentam incoerências com estudos clínicos e *in vitro*. Ao avaliar padrões de fratura e resistências à fratura, os dados obtidos tanto em estudos clínicos quanto *in vitro* costumam não corresponder claramente com o desempenho previsto computacionalmente. Visto que a perda de adesão entre dente e restauração antecede a falha catastrófica *in vitro*, a inclusão e entendimento desse comportamento em estudos computacionais pode se fazer necessário para melhor correlação com os dados experimentais. **Objetivos:** Elucidar a influência da perda de adesão em restaurações intracanais e suas consequências na distribuição e valores máximos de tensões. **Material e métodos:** Cinco diferentes tipos de restaurações intracanais foram avaliadas através da análise por elementos finitos: MP = núcleo metálico fundido; GP = pino de fibra de vidro; PP = pino metálico pré-fabricado; RE = *endocrown* em resina; CE = *endocrown* em cerâmica em corpo único. Dois preparos cervicais foram considerados: sem férula (f_0) e férula de 2 mm (f_1). A simulação foi realizada em três etapas: (1) todos os contatos colados; (2) falha de adesão entre coroa e dente; (3) falha de adesão entre coroa, pino intracanal e dente. Contatos friccionais e separação entre as interfaces foram modeladas onde a falha de adesão foi simulada. As razões de tensões obtidas pela teoria de Mohr-coulomb ($\sigma_{MC\ ratio}$) e fator de segurança em fadiga (SF) para dentina foram comparadas com valores disponíveis na literatura de resistência a fratura, vida em fadiga e padrões de fratura em dentes com restaurações intracanais. **Resultados:** Os valores de $\sigma_{MC\ ratio}$ não apresentaram diferenças entre os grupos na primeira etapa. A segunda etapa provocou aumento do $\sigma_{MC\ ratio}$ em região de férula quando comparado com a primeira etapa. Na terceira etapa, $\sigma_{MC\ ratio}$ e SF para os modelos f_0 foram altamente influenciados pelo material do material restaurador. Os modelos CE e RE apresentaram os maiores valores de $\sigma_{MC\ ratio}$ e menor SF. O grupo MP apresentou o menor $\sigma_{MC\ ratio}$ e maior SF. Os modelos f_1 não mostraram diferenças relevantes na terceira etapa. **Conclusão:** A análise por elementos finitos apresentou melhor semelhança à literatura quando o contato friccional para restaurações intracanais é simulado. Resultados de análises onde todos os contatos são simulados como unidos devem ser considerados com cautela.

Palavras-chave: Análise de Elementos Finitos. Dente. Fraturas por Fadiga. Falha de Restauração Dentária.

ABSTRACT

Computational stress analyses of intra-radicular restorations sometimes seem to contradict *in vitro* and clinical studies. When evaluating fracture patterns and ultimate strength, the obtained data from *in vitro* and clinical studies usually do not correspond to the behavior observed by computational methods. As the adhesion loss between tooth and restoration precedes the catastrophic failure *in vitro*, the addition and understanding of this behavior in computational studies could be necessary for better correlation to experimental data. **Objectives:** To elucidate the influence of debonding on stress distribution and maximum stresses for intra-radicular restorations. **Methods:** Five intra-radicular restorations were analyzed by finite element analysis: MP = metallic cast post core; GP = glass fiber post core; PP = pre-fabricated metallic post core; RE = resin endocrowns; CE = single piece ceramic endocrown. Two cervical preparations were considered: no ferule (f_0) and 2 mm ferule (f_1). The simulation was conducted in three steps: (1) intact bonds at all contacts; (2) bond failure between crown and tooth; (3) bond failure among tooth, post and crown interfaces. Contact friction and separation between interfaces was modeled where bond failure occurred. Mohr-coulomb stress ratios ($\sigma_{MC\ ratio}$) and fatigue safety factors (SF) for dentin structure were compared with published strength values, fatigue life, and fracture patterns of teeth with intra-radicular restorations. **Results:** The $\sigma_{MC\ ratio}$ was similar for all restorations types at first step. The second step increased $\sigma_{MC\ ratio}$ at the ferule compared to step 1. At the third step, the $\sigma_{MC\ ratio}$ and SF for f_0 models were highly influenced by post material. CE and RE models had the highest values for $\sigma_{MC\ ratio}$ and lower SF. MP had the lowest $\sigma_{MC\ ratio}$ and higher SF. The f_1 models showed no relevant differences among them at the third step. **Conclusion:** Finite element analysis most closely predicted failure performance of intra-radicular posts when frictional contact was modeled. Results of analyses where all interfaces are assumed to be perfectly bonded should be considered with caution.

Key-words: Finite Element Analysis. Tooth. Fractures, Stress. Dental Restoration Failure.

LISTA DE ILUSTRAÇÕES

LISTA DE TABELAS

LISTA DE ABREVIATURAS E SIGLAS

3D	-	*Three-dimensional*
CAD	-	*Computer-aided design*
CE	-	*Single piece ceramic endocrown*
Cu-Al	-	*Copper-aluminum*
f_0	-	*Non-ferule models*
f_1	-	*Ferule models*
FEA	-	*Finite element analysis*
GP	-	*Glass fiber post core*
GPa	-	*Gigapascal*
mm	-	*Millimeters*
MP	-	*Metallic cast post core*
MPa	-	*Megapascal*
N	-	*Newton*
PP	-	*Pre-fabricated metallic post core*
RE	-	*Resin endocrown*
SF	-	*Safety factor*
S-N	-	*Stress vs. Number of Cycles*
UCS	-	*Ultimate compressive strength*
UTS	-	*Ultimate tensile strength*
σ_{max}	-	*Maximum principal stress*
$\sigma_{MC\ ratio}$	-	*Mohr-coulomb stress ratio*
σ_{min}	-	*Minimum principal stress*

SUMÁRIO

1 INTRODUÇÃO

As análises computacionais de tensões em restaurações intracanais por vezes apresentam inconsistências com estudos clínicos e *in vitro*. Uma meta-análise sobre estudos *in vitro* de raízes dentais restauradas com núcleos metálicos fundidos ou pinos de fibra de vidro observou maior resistência à fratura para os núcleos metálicos fundidos (Zhou & Wang 2013). Contudo, trabalhos utilizando a análise por elementos finitos mostraram menores valores de tensão para restaurações com pinos de fibra de vidro, enquanto que outros trabalhos sugeriram valores de tensões similares em dente independentemente do material restaurador intracanal, o que pode ser controverso aos dados obtidos pela meta-análise supracitada (De Castro Albuquerque et al. 2003; Madfa et al. 2015; Sorrentino et al. 2007).

Quando avaliado os padrões de fratura, dados obtidos tanto em estudos clínicos quanto *in vitro* costumam não corresponder claramente com os campos de tensões mostradas pelos estudos com análise por elementos finitos (Figueiredo et al. 2015; Magne et al. 2017; Maroli et al. 2017). Experimentalmente, a maioria das fraturas relatadas por dentes restaurados com pinos de fibra de vidro são coronais (A. Alharbi et al. 2014; Akkayan & Canikliogly 1998; Akkayan & Gülmez 2002; Sirimai et al. 1999; Zhou & Wang 2013), sendo as fraturas verticais e infraósseas mais comuns em restaurações com núcleo metálico fundido (Akkayan & Canikliogly 1998; Butz et al.; Sidoli et al. 1997; Zhou & Wang 2013). Tal comportamento deve-se refletir nos campos de tensões observados computacionalmente, com valores máximos de tensões nos pontos provavelmente iniciais de fraturas, assim como apresentar direcionamento das tensões condizentes com o sentido de propagação da trinca (tensão máxima principal perpendicular ao sentido da trinca). No entanto, esses dados computacionais não apresentam grande correlação quando o dente e restauração apresentam comportamento da interface unido, tendo características de uma adesão perfeita entre os corpos (Figueiredo et al. 2015; Magne et al. 2017; Maroli et al. 2017; Santos-Filho et al. 2014; Veríssimo et al. 2014).

Aspectos importantes para o desempenho de restaurações intracanais são a qualidade e integridade da interface adesiva. Falhas primárias de adesão (separação do dente e coroa, gerando um espaço na interface entre os mesmo) são relatadas em estudos *in vitro* previamente às falhas catastróficas (Magne et al. 2017). As condições da interface adesiva são difíceis de analisar *in vitro* e especialmente *in vivo*. No entanto, a análise por elementos finitos é um método eficiente para estudar o efeito da adesão e o processo de falha de adesão nas tensões internamente presentes nos corpos (Schmitter et al. 2010). A análise por elementos finitos tem mostrado que a condição da adesão modifica significantemente a distribuição das tensões e seus valores máximos na estrutura dental (Santos et al. 2009; Santos et al. 2010). Contudo, a falha de adesão não é regularmente considerada nas simulações computacionais, onde a maioria das análises considera apenas a situação com perfeita união entre os corpos (*bonded contact*), mesmo quando núcleos metálicos fundidos são analisados (De Castro Albuquerque et al. 2003; Maroli et al. 2017; Sorrentino et al. 2007; Veríssimo et al. 2014).

Fraturas dentais são também influenciadas pelo tipo de carregamento aplicado durante os estudos. A maioria das análises utilizam carregamentos quase-estáticos, que propiciam a formação das tensões mais aplicáveis para os casos de resistência à fratura. Estudos de resistência à fratura oferecem informações cruciais sobre a resistência que o elemento dental apresenta sob uma determinada condição de carregamento. No entanto, estruturas podem falhar sob o carregamento intermitente levando às fraturas por fadiga (Rodríguez-Cervantes et al. 2011). O dano acumulado provocado pela fadiga pode implicar em um processo progressivo de falha no tecido dentário, assim como na interface entre os materiais restauradores. Como a separação também afeta a distribuição de tensões e os padrões de fraturas, é importante considerar essa condição quando se faz comparações entre estudos de análise por elementos finitos, *in vitro* e *in vivo* (Santos et al. 2010).

Dentre as técnicas para restaurações intracanais, o núcleo metálico fundido e o pino de fibra de vidro apresentam grande número de estudos comparativos (Zhou & Wang 2013). Além disso, outras técnicas estão disponíveis, como a utilização de pinos metálicos pré-fabricados ou mesmo a não utilização de pinos intracanais através da técnica de *endocrown*, onde o preparo intracanal está restrito ao terço cervical radicular. Estudos *in vitro* mostraram comportamentos similares entre pinos de fibra de vidro e pinos metálicos pré-fabricados (Maroli et al. 2017), além de menor resistência à fratura para as técnicas de *endocrown*, com maior índice de fraturas cervicais ou soltura da peça protética (perda de adesão) (Hayes et al. 2017; Magne et al. 2017). O comportamento das fraturas também está relacionado com o módulo de elasticidade dos materiais utilizados para restauração (Akkayan & Gülmez 2002; Butz et al.; Martínez-Insua et al. 1998; Sidoli et al. 1997).

Com isso, o objetivo desse estudo é elucidar a influência do efeito da perda de adesão nos campos de tensão e respectivos valores máximos em restaurações intracanais. Cinco diferentes técnicas restauradoras (núcleo metálico fundido, pino de fibra de vidro reembasado por resina composta, pino metálico pré-fabricado reembasado por resina composta, *endocrown* em resina e *endocrown* em cerâmica em corpo único) com dois preparos cervicais (sem férula e férula de 2 mm) foram simulados e comparados com a literatura a respeito da resistência à fratura, vida em fadiga e padrões de fratura para restaurações intracanais. A hipótese de pesquisa é que a falha de adesão criará campos de tensões e indicadores de fratura que melhor representam a resistência à fratura e à fadiga para restaurações intracanais do que se fossem simulados com interfaces apresentando perfeita união. Os resultados poderão auxiliar no entendimento da mecânica existente na fratura de elementos dentais restaurados intrarradicularmente e a influência de fatores como: qualidade da interface adesiva; material restaurador e geometria do preparo, assim como contribuir para a validação da análise por elementos finitos para o problema em questão.

2 ARTIGO: Should adhesive debonding be simulated for intra-radicular post stress analyses?

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Highlights

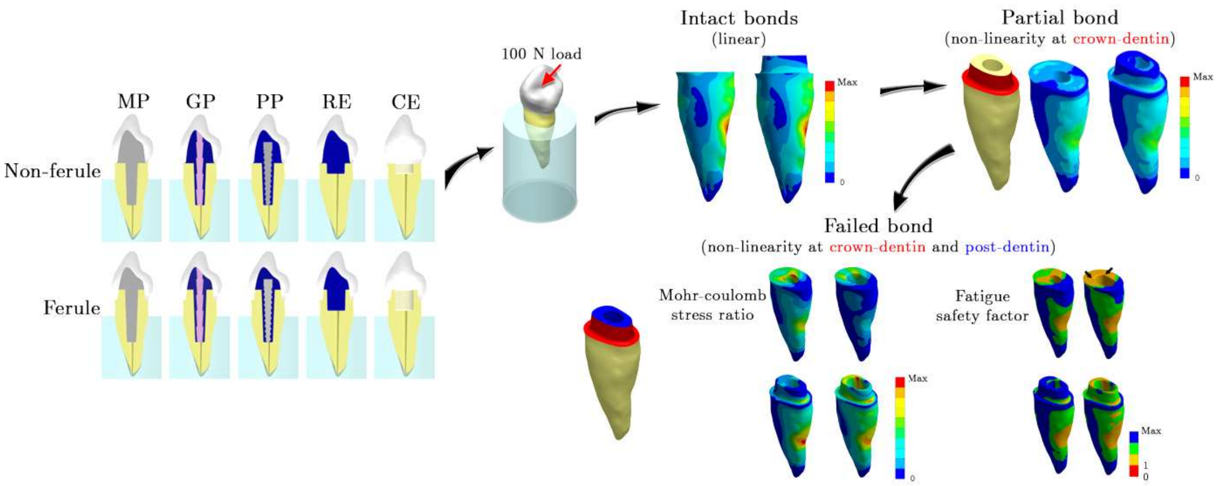
- FEA for perfectly bonded intra-radicular post does not match published in vitro data.
- Frictional contact is recommended for realistic results of intra-radicular post FEA.
- This study proposes a guideline for intra-radicular post simulation in FEA.

Abstract

Objectives: Elucidate the influence of debonding on stress distribution and maximum stresses for intra-radicular restorations. **Methods:** Five intra-radicular restorations were analyzed by finite element analysis (FEA): MP = metallic cast post core; GP = glass fiber post core; PP = pre-fabricated metallic post core; RE = resin endocrowns; CE = single piece ceramic endocrown. Two cervical preparations were considered: no ferule (f_0) and 2mm ferule (f_1). The simulation was conducted in three steps: (1) intact bonds at all contacts; (2) bond failure between crown and tooth; (3) bond failure among tooth, post and crown interfaces. Contact friction and separation between interfaces was modeled where bond failure occurred. Mohr-coulomb stress ratios ($\sigma_{MC\ ratio}$) and fatigue safety factors (SF) for dentin structure were compared with published strength values, fatigue life, and fracture patterns of teeth with intra-radicular restorations. **Results:** The $\sigma_{MC\ ratio}$ showed no differences among models at first step. The second step increased $\sigma_{MC\ ratio}$ at the ferule compared to step 1. At the third step, the $\sigma_{MC\ ratio}$ and SF for f_0 models were highly influenced by post material. CE and RE models had the highest values for $\sigma_{MC\ ratio}$ and lower SF. MP had the lowest $\sigma_{MC\ ratio}$ and higher SF. The f_1 models showed no relevant differences among them at the third step. **Significance:** FEA most closely predicted failure performance of intra-radicular posts when frictional contact was modeled. Results of analyses where all interfaces are assumed to be perfectly bonded should be considered with caution.

Key-words: Finite element method; finite element analysis; post-core; fiber post; endocrown; non-linear analysis; fracture; fatigue; tooth; root; ultimate strength; safety factor; mohr-coulomb; frictional contact.

Graphical abstract



1. Introduction

Computational stress analyses of intra-radicular restorations sometimes seem to contradict *in vitro* and clinical studies. A meta-analysis of *in vitro* studies evaluating roots restored with metal or fiber posts showed higher fracture strengths with metal posts [1]. However, several clinical systematic reviews comparing intra-radicular restorations showed inconclusive or contradictory results [2–8]. Some finite element analyses (FEA) showed lower stress values for fiber post restorations while others have suggested similar stress values regardless of post material [9–11]. Fracture patterns observed in clinical and *in vitro* studies also do not always clearly correspond with the stress fields and orientations shown in FEA studies [6,12,13].

An important aspect for intra-radicular post performance is the quality and integrity of the adhesive interface. Primary adhesion failures (causing a slight separation between crown and root) are reported in *in vitro* studies prior to catastrophic failures [12]. Adhesive conditions are difficult to analyze *in vitro* and especially *in vivo*, but FEA is an eminent method to study the effect of bonding and the process of debonding on internal stress conditions. FEA has shown that the presence of adhesion significantly changes stress distributions and stress values in the tooth structure [14]. Yet, debonding is not regularly considered in computational simulations because most analyses only consider perfect bonding or 'bonded contact', even for metal posts [9,10,13,15]. Adhesion failure studies that did simulate unbonded contacts have shown better correlation with fracture tendency reported in the literature than bonded interfaces, suggesting that models simulating only perfectly bonded contacts in root fracture studies may lead to false conclusions [14,16,17].

Tooth fractures are also influenced by the type of loading. Most analyses apply quasi-static loads, which provide stress information most applicable for ultimate strength considerations. Ultimate strength offers crucial information about the maximum resistance to fracture of restored teeth under a specific static loading condition. However, structures may fail under lower loads when repetitive loading leads to fatigue crack propagation [18]. Fatigue damage accumulation implies that failure can be a process of progressive separation within or between materials. Such separations also affect stress distributions and fracture patterns, and are thus important to consider when making comparisons between FEA outcomes and experimental or clinical observations [14].

Therefore, the aim of this study was to elucidate the influence of the debonding effect at stress fields and maximum stresses at intra-radicular restorations. Five different intra-radicular restorations (metallic cast post, glass fiber post, pre-fabricated metallic post, resin endocrown and ceramic endocrown) with two distinct cervical preparations (no ferule or 2 mm ferule) were simulated and compared to the literature about ultimate strength, fatigue life, and fracture pattern of intra-radicular restorations. The hypothesis was that debonded interfaces create stress fields and fracture indicators that can better represent strength and fatigue failure behavior for intra-radicular restorations than if they would be simulated as bonded interfaces.

2. Materials and methods

A three-dimensional (3D) single-rooted human tooth model was obtained from an open-access online database [19]. The tooth was resized to satisfy standard dimensions defined in two experimental studies (root length of 14 mm from enamel junction to the apex, 5.0 mm mesio-distal width and 7.0 mm bucco-lingual width at enamel junction) [12,15]. Models were created with two cervical conditions: no ferule (f_0) or 2 mm ferule (f_1) [12,15]. The endodontic treatment was modeled taking into account the geometry of a 40/06 rotary file. Three-dimensional geometries and assemblies were created with a computer-aided design (CAD) software (SolidWorks 2010, Concord, MA, USA). Ten singular 3D assemblies were created comprising a resin cylinder, tooth root, internal retention, and prosthetic crown. The internal retentions were: metallic cast post core (MP), glass fiber post core (GP), pre-fabricated metallic post core (PP), resin endocrowns (RE) and single piece ceramic endocrowns (CE) (**Figure 1**). The GP and PP were anatomically relined with composite resin.

Each root was embedded in a 14 × 20 mm (diameter × height) polystyrene resin cylinder, keeping 3 mm of the cervical root exposed. The assemblies were imported into finite element analysis software (ANSYS Workbench 11, Ansys Inc., Pittsburg, PA, USA). The assemblies were meshed with tetrahedral elements, featuring 10 nodes and 6 degrees of freedom. The mesh was checked for element quality and refined in areas of interest, resulting in approximately 290,000 elements and 410,000 nodes per model.

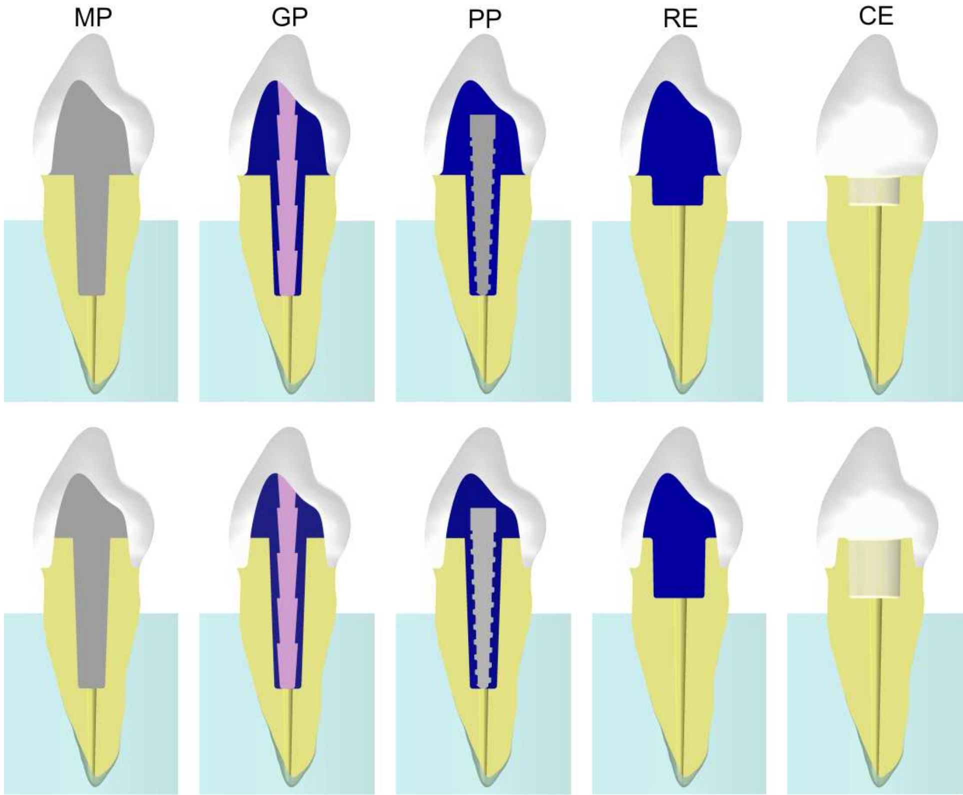


Figure 1. Illustration of the 10 restoration configurations. Lithium dissilicate (white); Dentin (yellow); Metal posts (grey); Glass fiber post (light purple); Composite resin (dark blue); Polystyrene resin (light blue). MP = metallic cast post core; GP = glass fiber post core; PP = pre-fabricated metallic post core; RE = resin endocrowns; CE = single piece ceramic endocrowns. The upper images are the non-ferule condition while the bottom images are the 2 mm ferule condition.

Elements were assigned material properties. All materials were considered isotropic, except for the orthotropic glass fiber post, and properties were homogeneously distributed and linear elastic. These parameters are well-established at the literature for FEA analysis, being the orthotropic behavior promoted by the fibrous composition of glass fiber post [20–25]. The material properties were obtained from published data (**Table 1**).

A total load of 100 N was applied in the lingual cingulum at 45° to the long axis of the tooth, according to test parameters used in FEA and experimental studies [13,15,26]. The models were constrained by fixing all six degrees of freedom at the bottom and lateral surface of the resin cylinders.

Table 1. Material properties.

Material	Elastic modulus (GPa)	Poisson's ratio	Shear modulus (GPa)
Dentin [20]	18	0.31	
Polystyrene resin [21]	13.5	0.31	
Composite resin [21]	15.8	0.24	
Stainless steel (PP) [22]	193	0.30	
Cu-Al Alloy (MP) [23]	109	0.33	
Lithium dissilicate [24]	96	0.23	
Glass fiber post* [25]	x = 37	xy = 0.34	xy = 3.54
	y = 9.5	yz = 0.27	yz = 14.57
	z = 9.5	xz = 0.34	xz = 3.54

*x-axis is in the glass fiber post long axis.

2.1. Bonding failure at contacting surfaces

Bonding conditions can be expected to vary and evolve, creating conditions where bonded and non-bonded regions may be present simultaneously [14]. This study therefore simulated three bonding conditions, varying from all bonded to completely failed bonds. Each situation presents a specific fracture risk, depending on post material or ferule presence. To simulate bonding changes, a subroutine was programmed for each step using the 'ekill' element death command. This command automatically changed bonded contact into (unbonded) frictional contact at the end of each load step, as described in **Table 2**. Non-cited contacts were set to remain bonded in all steps. The first step was 'Intact Bond', the second 'Partial Bond' and the third 'Failed Bond'. The contact formulations were set to Pure Penalty and Augmented Lagrange for bonded and frictional contacts, respectively. All contacts were symmetric and no gaps or penetrations were allowed between surfaces at initial contact situation. Contact pressure at crown-dentin and post-dentin contact regions was evaluated to identify adhesion failure. As the frictional coefficients between these materials were not known, 0.5 was used for MP-dentin and 0.3 for all other frictional contacts.

Table 2. Contact configuration by steps.

Contact pair (dentin to ...)	**Step***		
	1st	**2nd**	**3rd**
Resin cylinder (all groups)	Frictional	Frictional	Frictional
Crown (except of CE group)	Bonded	Frictional	Frictional
GP, PP and RE	Bonded	Bonded	Frictional
CE	Bonded	-	Frictional
MP	Frictional	-	Frictional

*CE and MP were simulated in two steps. The post and crown are the same part in CE group and MP is already in frictional contact at the first step. GP = glass fiber post core; PP = pre-fabricated metallic post core; RE = resin endocrowns; CE = single piece ceramic endocrowns; MP = metallic post core.

2.2. Failure theory (static analysis)

To assess the risk of debonding, shear or tensile stresses at each interface should be divided by their respective shear or tensile strengths [8]. The tensile stress across the interface in this study were analyzed by the pressure values provided by the contact tool in ANSYS Workbench. Negative pressure at contacting surfaces indicated that surfaces want to separate (tensile stress). Therefore, it was assumed that the risk of debonding was higher as the negative pressure values increased.

Mohr-Coulomb failure theory was used to analyze the Stress Ratio in dentin. This theory is typically used to predict fracture in brittle materials under quasi-static loading. The Mohr-Coulomb stress failure theory states that failure occurs when the combination of the maximum and minimum principal stress equals or exceeds the stress limits (tensile or compressive strengths). The theory compares the maximum stress (maximum tensile) to the material's tensile limit and the minimum stress (maximum compression, because compressive stress is negative) to the material's compressive limit. The Mohr-Coulomb Stress Ratio ($\sigma_{MC\ ratio}$) is expressed as:

$$\sigma_{MC\,ratio} = \frac{\sigma_{max}}{UTS} + \frac{\sigma_{min}}{UCS} \tag{1}$$

where UTS is the material's Ultimate Tensile Strength and UCS is the Ultimate Compressive Strength. If the $\sigma_{MC\ ratio}$ value exceeds 1, the material will fail. The dentin UTS and UCS were 96 MPa[27] and 295 MPa[28], respectively.

2.3. Fatigue analysis

For stress-life fatigue simulation, a Stress vs. Number of Cycles to Failure curve (S-N curve) was input for the dentin properties (**Figure 2**) [29]. Among the mean stress theory options available in Ansys Workbench 10, the Goodman theory was selected for the fatigue analysis because it reportedly correlates well for high-cycle fatigue ($>10^5$ cycles) [18,30]. The Goodman approach associates maximum principal stress values from quasi-static analysis and the S-N data to estimate fatigue life (in cycles) of dentin. A strength reduction factor 0.865 was used for reliability of

95% [31]. The planned life entered for dentin was 1.2×10^6 cycles, which simulates approximately 5 years of clinical service [26]. A safety factor (SF), which indicates the dentin parts that are more susceptible to fatigue failure, was calculated for the estimated fatigue life as:

$$SF = \frac{estimated\ life}{1.2 \times 10^6} \quad (2)$$

where SF < 1 indicates dentin survival lower than planned life and the probable site of crack initiation.

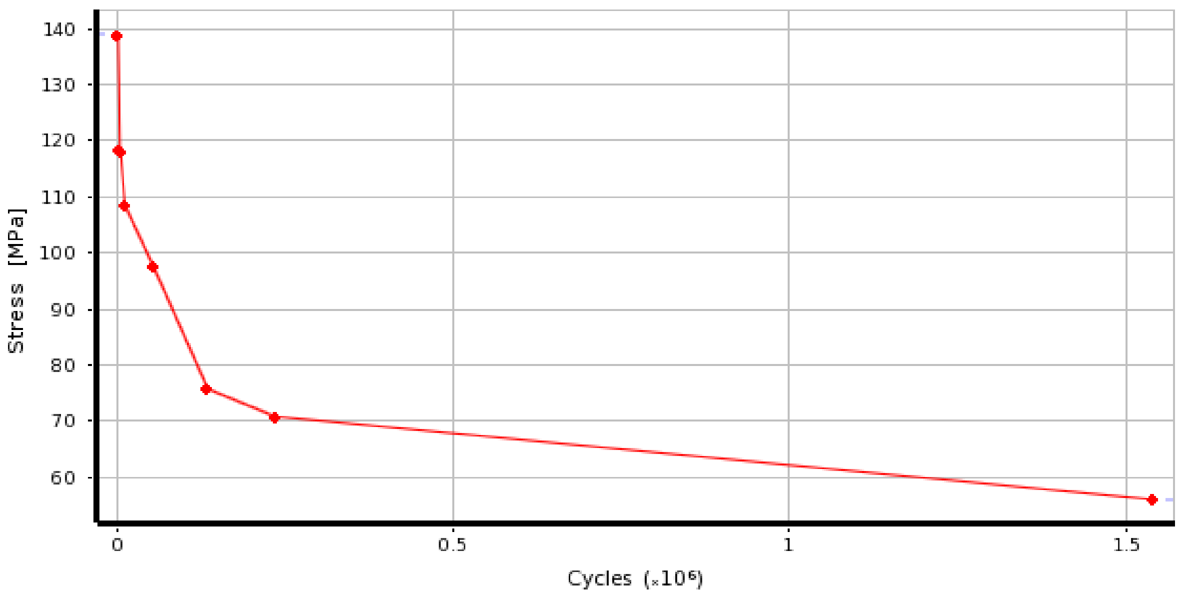


Figure 2. S-N Curve of dentin.

3. Results

3.1. Intact bonds (1st step)

The single-body behavior produced by bonded contact led to similar stress results in dentin, even with different post materials or cervical preparation, with $\sigma_{MC\ ratio} = 0.31 \pm 0.003$ (mean ± standard deviation). The highest $\sigma_{MC\ ratio}$ was found at the external root surface for all groups. The $\sigma_{MC\ ratio}$ extended also to cervical preparation and buccal region with lower values (**Figure 3**).

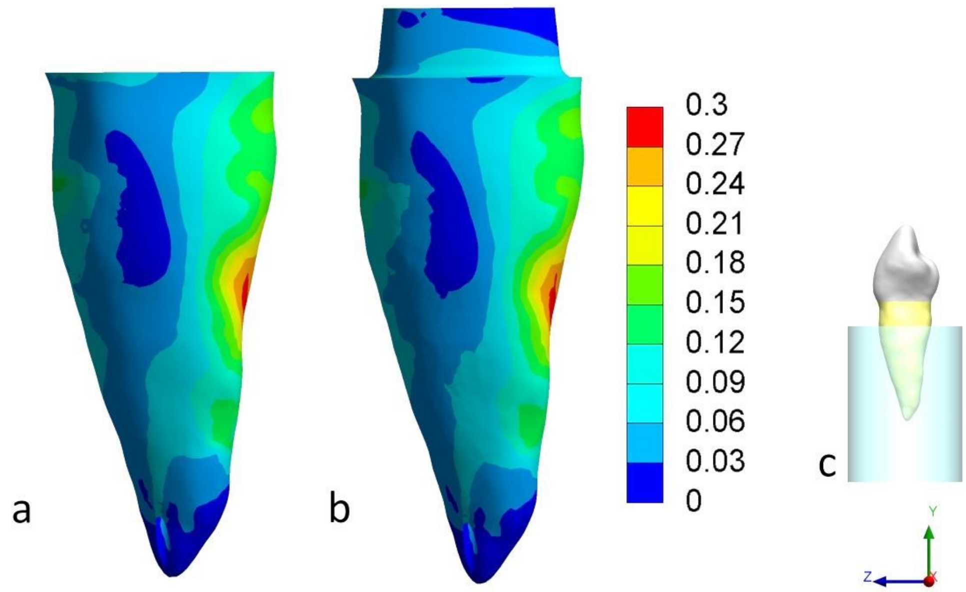


Figure 3. General representation Mohr-Coulomb stress ratio in dentin at 1st step. Groups did not show relevant differences at stress fields. a) f_0 models; b) f_1 models and c) viewpoint. The $\sigma_{MC\ ratio}$ is color coded varying from 0 to 0.3.

Despite the similar stress ratios, the groups showed different pressures at the dentin-crown interfaces, which were influenced by post material and ferule. The GP, PP and RE f_0 models showed a negative pressure (indicating a force that would cause bodies to separate) ranging from 15 to 25% higher than their respective f_1 pair. In MP models, f_0 had negative pressure 141% higher than f_1. The exception was CE with negative pressure 2.5% lower at f_0 (**Figure 4**).

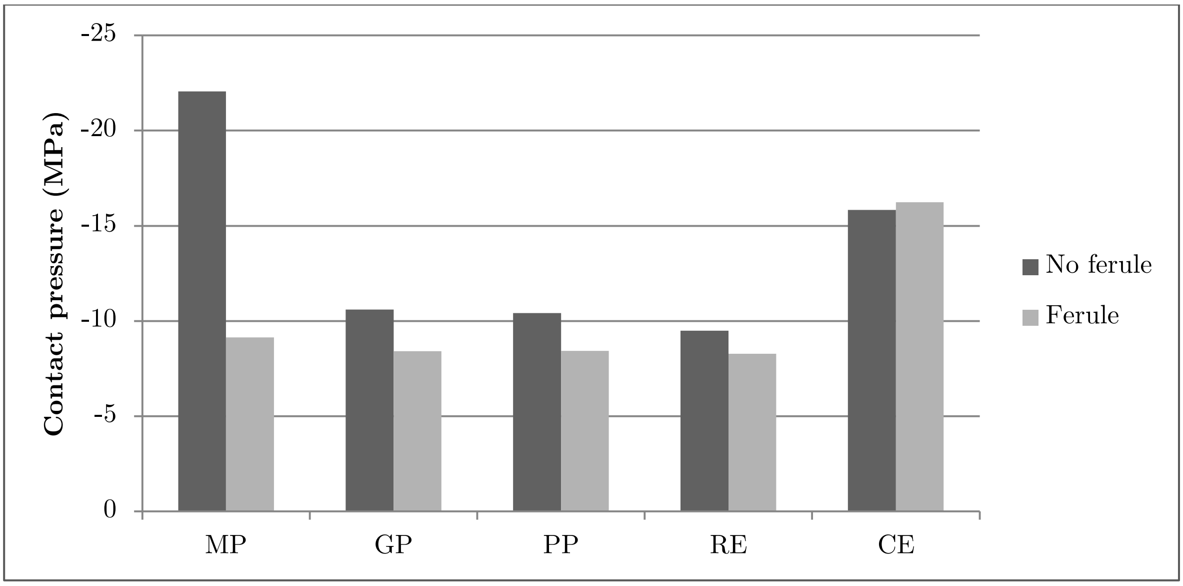


Figure 4. Pressure at contact interface of dentin and crown at 1st step. MP = metallic cast post core; GP = glass fiber post core; PP = pre-fabricated metallic post core; RE = resin endocrowns; CE = single piece ceramic endocrowns.

3.2. Partial bond (2nd step)

The Partial Bond step simulates a frictional contact between crown-dentin and bonded contact between dentin-retention posts. This step was not considered for MP group (post core is already in frictional contact since 1st step) and CE (crown and post are a single-body).

The bonding failure at the dentin-crown interface hardly affected the $\sigma_{MC\ ratio}$ for f_0 models from 1st to 2nd steps. However, the stress fields changed substantially for f_1 models when compared to 1st step, with f_1 models showing a high stress ratio at the ferule also. The stress distributions along the root were similar for 1st and 2nd steps, with the same maximum values. The post material hardly affected the stress distributions at the external dentin surface for GP, PP and RE groups (**Figure 5**).

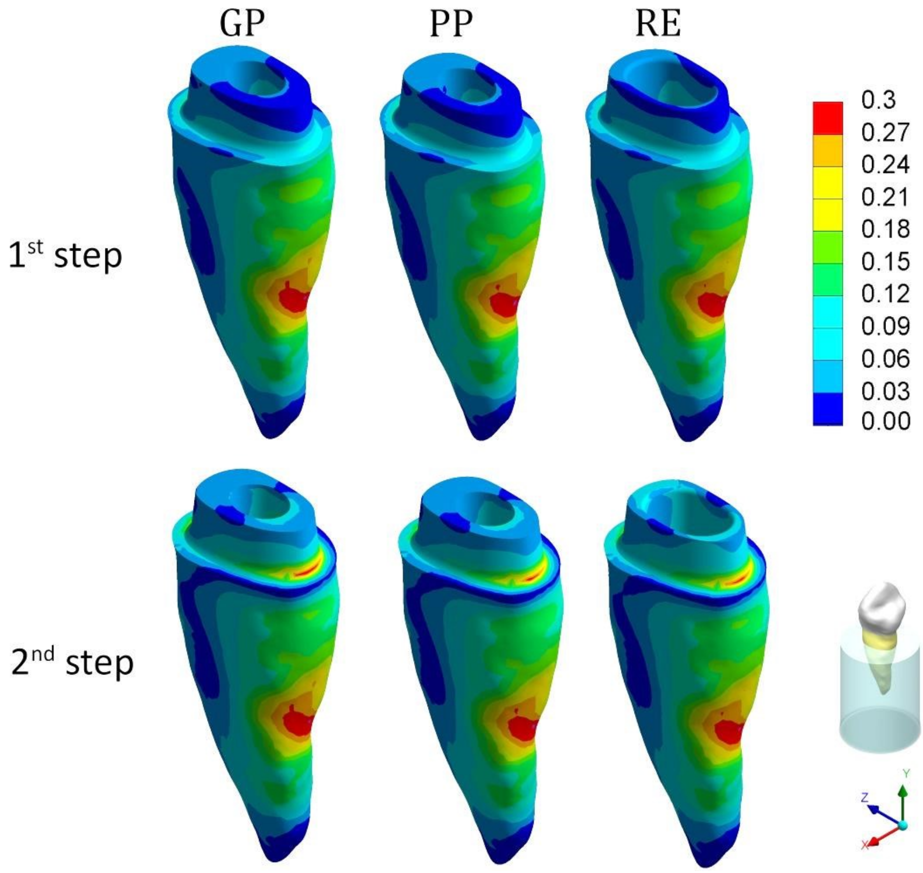


Figure 5. Mohr-Coulomb stress ratio in dentin showing differences at the ferule for GP, PP and RE for 1^{st} and 2^{nd} step. GP=glass fiber post core; PP=pre-fabricated metallic post core; RE=resin endocrowns.

The models showed differences in contact pressure at dentin-internal post interfaces, influenced by post and ferule. The f_0 models showed a negative pressure ranging from 38 to 111% higher than their respective f_1 pair. The GP and PP showed values lower than those for the endocrown models (**Figure 6**).

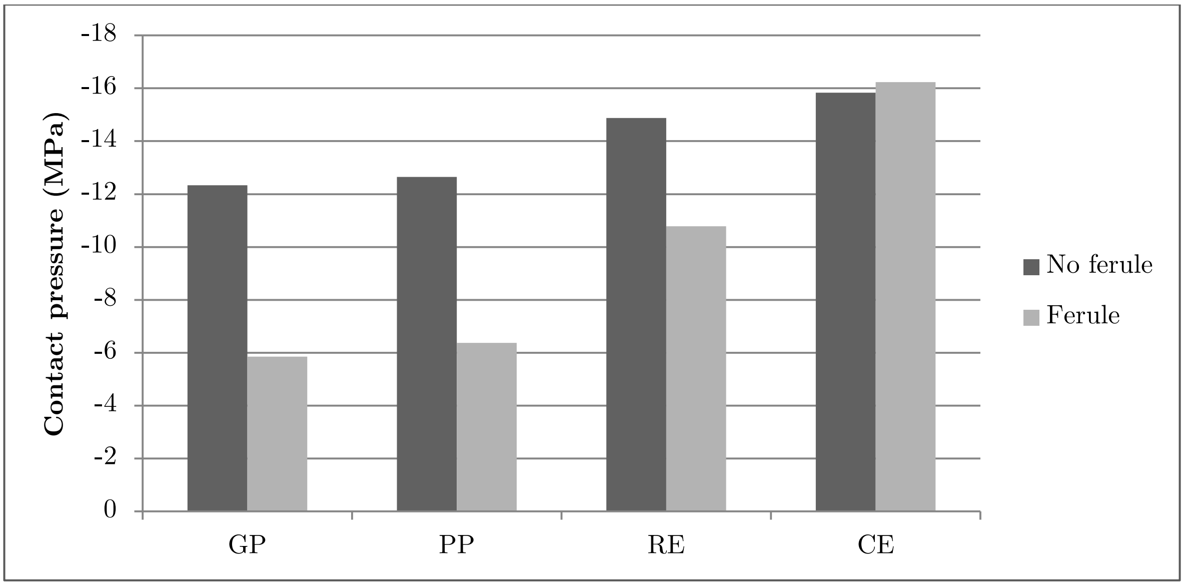


Figure 6. Pressure at contact interface of dentin and internal post in 2nd step for GP, PP and RE. CE values are the same of 1st step. GP=glass fiber post core; PP=pre-fabricated metallic post core; RE=resin endocrowns; CE=single piece ceramic endocrowns.

3.3. Failed bond (3rd step)

Bond failure at dentin-crown and dentin-post led to changes in stress distributions for all models. All f_0 models showed transition of the higher $\sigma_{MC\ ratio}$ values to the cervical region, at the root canal surface (**Figure 7**). The $\sigma_{MC\ ratio}$ was substantially higher than in the 1st and 2nd step. The $\sigma_{MC\ ratio}$ of f_0 MP was 30% higher than the f_1 MP, while GP and PP had $\sigma_{MC\ ratio}$ 99% and 94% higher, respectively.

RE and CE models where the most influenced by bond failure, with increases of 249% and 235% in $\sigma_{MC\ ratio}$, respectively. Both models had a $\sigma_{MC\ ratio}$ higher than 1, indicating a possible failure due to stresses exceeding the UTS or UCS of the dentin (**Figure 8**).

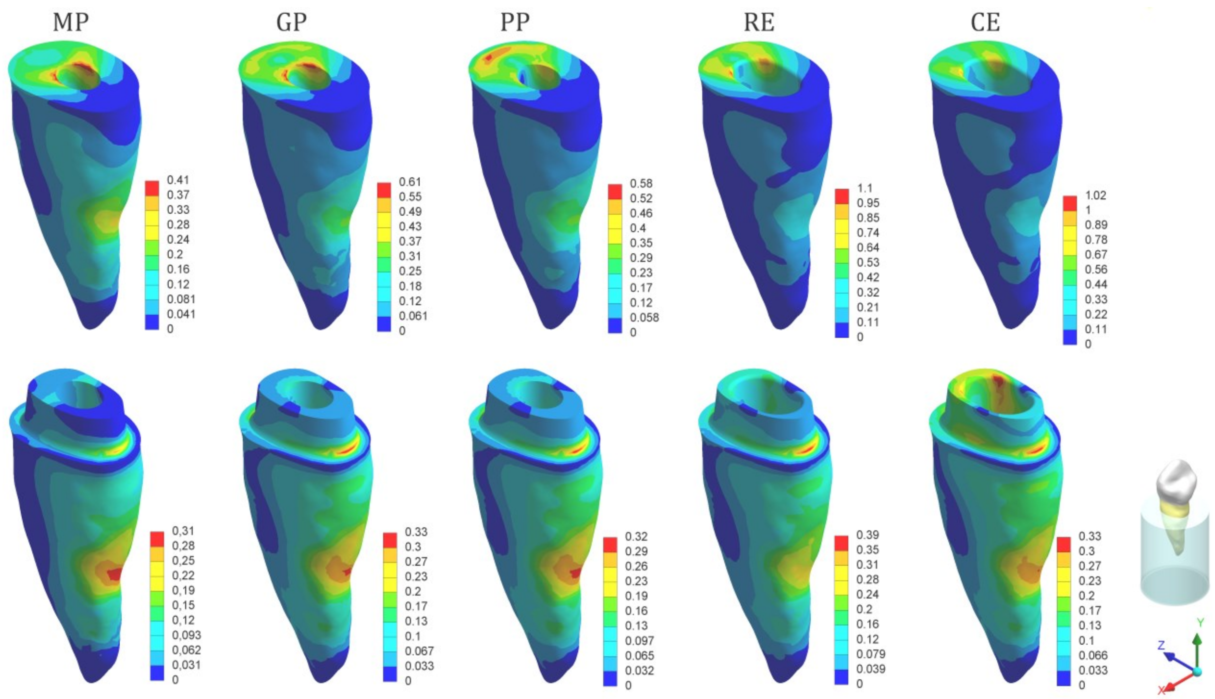


Figure 7. Mohr-Coulomb stress ratio in dentin at 3rd step (Failed Bond). MP = metallic cast post core; GP = glass fiber post core; PP = pre-fabricated metallic post core; RE = resin endocrowns; CE = single piece ceramic endocrowns.

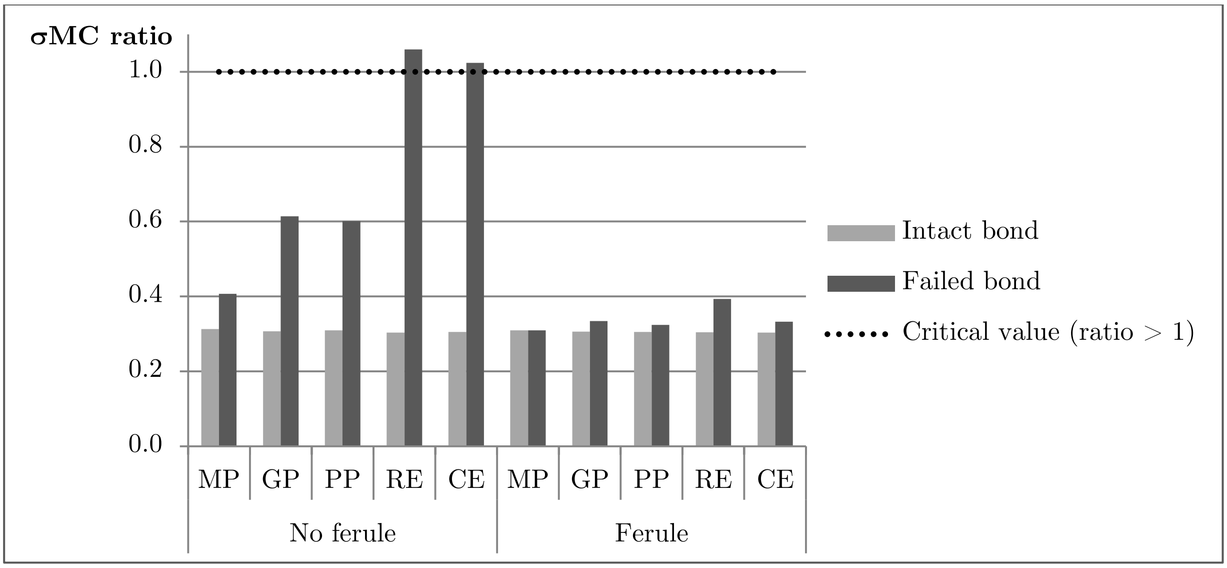


Figure 8. Mohr-Coulomb stress ratio in dentin at 1st and 3rd step. A value over 1.0 indicates fracture. MP = metallic cast post core; GP = glass fiber post core; PP = pre-fabricated metallic post core; RE = resin endocrowns; CE = single piece ceramic endocrowns.

The f_1 models showed slight changes in stress fields compared to f_0, with increases of $\sigma_{MC\ ratio}$ ranging from 0% (MP) to 29% (RE) higher. Higher values of $\sigma_{MC\ ratio}$ were found at the ferule region, in root canal, in direction to the external root surface. The CE model had the higher value in the internal region of ferule (**Figure 7**). The differences from steps 1 and 2 were less severe for f_1 models, with no values indicating catastrophic failures for any case (**Figure 8**).

A complete overview of stress field changes is presented in a supplementary video (**Video 1**).

3.4. Fatigue analysis

At the 1st and 2nd steps (with simulation of no or partial bond failure) the models did not show relevant differences in safety factors, regardless of post material and/or ferule presence. However, at the 3rd step (complete bond failure), the safety factors were clearly influenced by post material and ferule presence (**Figure 9**).

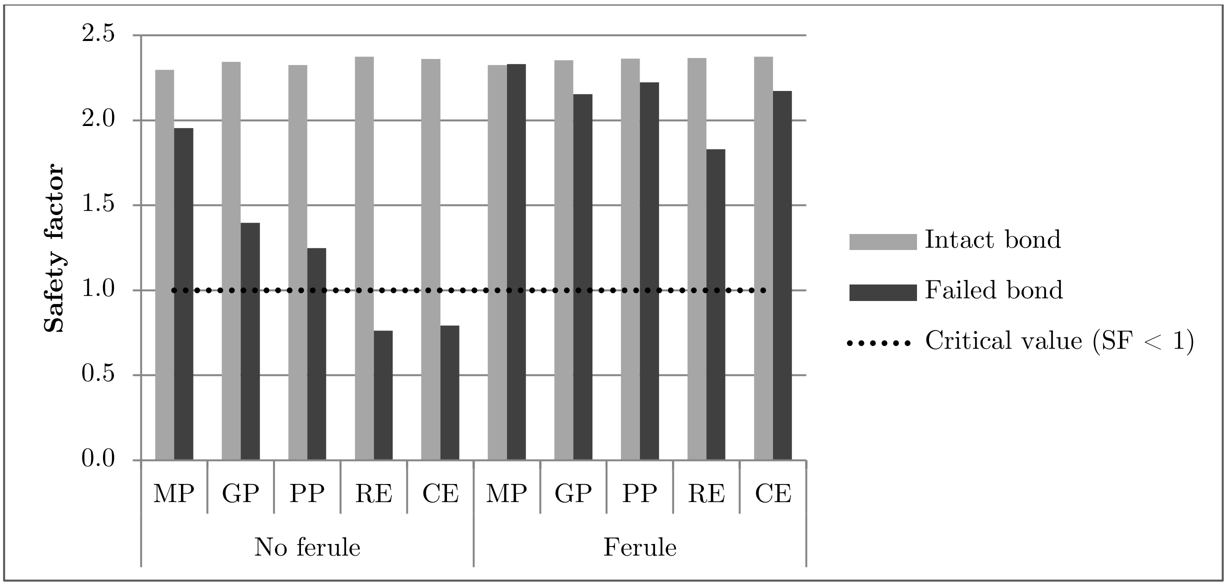


Figure 9. Safety factor for fatigue analysis at 1st and 3rd step. A value under 1.0

indicates crack initiation before planned life. MP = metallic cast post core; GP = glass fiber post core; PP = pre-fabricated metallic post core; RE = resin endocrowns; CE = single piece ceramic endocrowns.

At the 3rd step, all f_0 models showed lower SF values at the cervical region, at the root canal surface, towards the external surface (**Figure 10**). The MP f_0 group had a decrease of 15% in SF compared to MP f_1. GP and PP were 40% and 46% lower, respectively. A safety factors less than 1 were found for the RE and CE f_0 models, which indicates the potential for crack initiation from the internal region (red area, **Figure 10**); these models suffered an SF reduction of 68% and 66%, respectively.

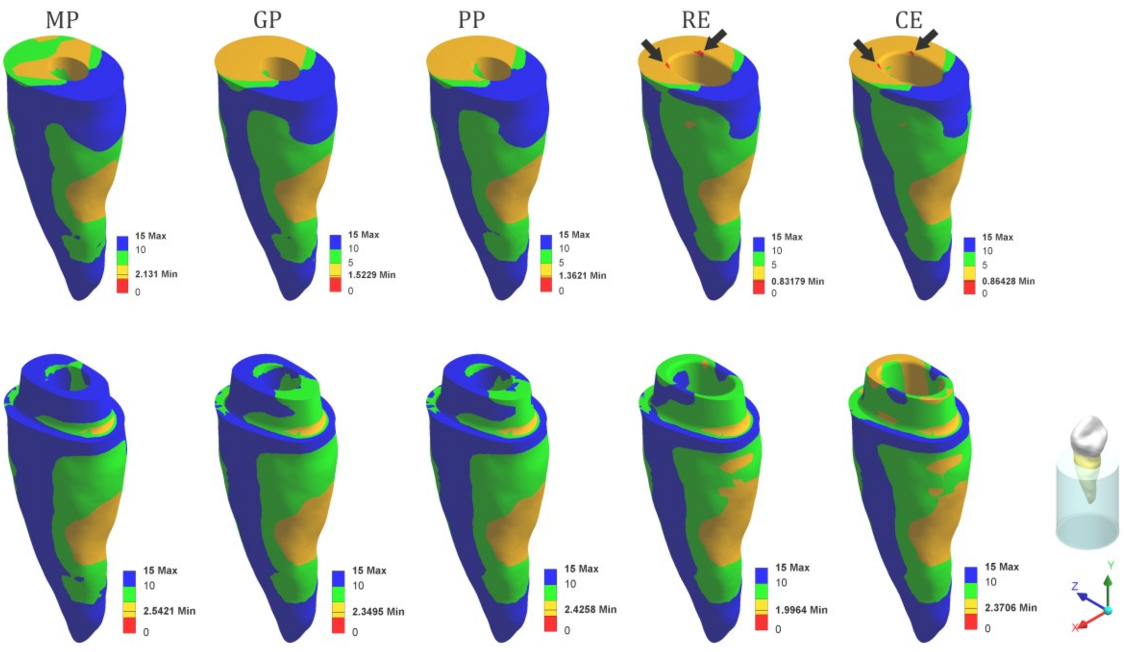


Figure 10. Safety factor (SF) map of fatigue analysis at 3rd step. A value less than 1.0 (red color) indicates predicted crack initiation before planned life. Black arrows indicate the potential fracture initiation site. MP = metallic cast post core; GP = glass fiber post core; PP = pre-fabricated metallic post core; RE = resin endocrowns; CE = single piece ceramic endocrowns.

The f_1 models showed slight changes with lower values in the ferule region and external to the root surface. Exception was CE, which had the lower value internal to the ferule. The reduction in SF for f_1 models from the 1^{st} to 3^{rd} step varied from 0% (MP) to 23% (RE).

Almost all models reached the planned life, except RE f_0 and CE f_0 at the 3^{rd} step (48,095 and 74,598 cycles, respectively). The FEA indicated higher life cycles for ferule models compared to the models without ferule.

4. Discussion

This study evaluated the hypothesis that calculating stress distributions and fracture indicators for intra-radicular restorations is more realistic if debonded interfaces are simulated. The results showed that the state of bonding substantially affected stress distributions and fracture indicators. To confirm the hypothesis, our finite element results must be compared with failure observations from experimental and clinical studies.

Several studies reported that the use of posts with high elastic modulus increase stresses at cement interface, with the possibility of post debonding or root fracture [32–35]. In the 1^{st} step, the crown-dentin interface was analyzed. All models showed interfacial stresses that were proportional to the elastic modulus of the post or endocrown (the higher the elastic modulus, the higher the stresses at interfaces), which is in agreement with the literature [32–35]. The f_1 models showed lower stress values and consequently lower debonding risk than f_0 models. This behavior was reported in experimental tests where 81% of f_0 and 14% of f_1 were involved in primary failure (or gap) occurring between crown and dentin prior to fracture [12,17]. This gap is probably caused by adhesion failure between crown, dentin, and post, leading to crown dislodgement. The MP f_0 model showed the highest tensile stresses in the interface, suggesting the dentin-crown interface was most prone to failure (**Figure 4**). The ceramic endocrowns were the second group more prone to adhesive failure. The bonding failure risk at the 2nd step was lower for f_1 models, with GP and PP showing similar values (**Figure 6**).

Experimental fractures can be classified as repairable or non-repairable (catastrophic failures). Repairable fractures are those up to root cervical third or post fractures in the core structure. Non-repairable fractures involve fractures reaching the middle and apical thirds [12,13]. In this work, the fracture risk was evaluated by $\sigma_{MC\ ratio}$, where higher fracture risks are indicated by higher $\sigma_{MC\ ratio}$.

In the 1st step no differences in fracture risk were found among the different models (same $\sigma_{MC\ ratio}$). The highest $\sigma_{MC\ ratio}$ was at external lingual surface at the middle third of the root in all models (**Figure 3**). The same pattern of $\sigma_{MC\ ratio}$ fields and peaks would suggest similar strength and failure modes for all groups, with fractures at the middle third external lingual surface. However, this does not occur in *in vitro* experiments [1,12–14,36]. The observed fractures *in vitro* typically begin at the cervical region, near the post core, and extend to the external cervical, middle or apical surface, depending of the post material and presence of ferule. Usually, metal posts have a higher incidence of affecting middle or apical third, while GP, PP and endocrowns affect the cervical third more [12,17,36,37]. This observation confirms that a perfectly bonded condition is not an appropriate assumption for investigating failure behavior in FEA [14,16,17].

No changes in maximum $\sigma_{MC\ ratio}$ were observed from 1^{st} to 2^{nd} step (**Figure 5**). Besides the same maximum $\sigma_{MC\ ratio}$ from 1^{st} step, the f_1 models suffered a substantial change in $\sigma_{MC\ ratio}$ fields, indicating a high stress ratio at the ferule (**Figure 5**). The higher stress at the ferule suggests higher fracture risk at the cervical third, including the ferule in the fracture site, similarly to what was observed in *in vitro* experiments [12,17]. Also, no relevant differences were observed among the post materials, which is in agreement with an observation that ferule presence has more effect on fracture resistance than post material [12].

In the f_0 models at 2^{nd} step the $\sigma_{MC\ ratio}$ peaks were still in middle third of root with no influence of post materials. However, the literature shows influence of post materials in fracture patterns and ultimate strengths in absence of ferule, with higher incidence of catastrophic fractures in MP post than other posts and higher ultimate strengths for MP [12,13,36]. This observation suggests that the partially debonded condition should be used with caution, as it agrees with the literature only for ferule models.

As the $\sigma_{MC\ ratio}$ of 2^{nd} step comprises only three groups, the 3^{rd} step was compared directly to the 1^{st} step allowing comparison among all post models. The f_1 models had a slight increase in $\sigma_{MC\ ratio}$ from previous steps to 3^{rd} step, with the highest values for endocrown models and no relevant influence by post materials (similar to 2nd step). The ferule effect in 3rd step was also in agreement with *in vitro* literature, having more effect on the stress distribution than post material (**Figure 8**) [12].

For the f_0 models, changes in the $\sigma_{MC\ ratios}$ were clearly different and highly influenced by post materials when comparing the 1st and 3rd steps (**Figure 8**). The f_0 MP model showed the lowest stress ratio, followed by PP, GP and endocrowns, in agreement to fracture strength tests, where the MP groups showed higher fracture strength [13,36]. Also, an *in vitro* study with similar experimental design reported a mean fracture strength of 696.6 (MP), 450.3 (GP), 463.0 (PP), and 218.9 N (RE) [13], which corresponds well with the $\sigma_{MC\ ratios}$ predicted in our study (0.41(MP), 0.61 (GP), 0.60 (PP) and 1.06 (RE)). The f_0 models showed a higher $\sigma_{MC\ ratio}$ at the cervical region of the internal root canal, suggesting potential fracture initiation at the root cervical third, as suggested in the literature [1]. Non-ferule models usually lead to more favorable fractures (fractures in the cervical third or post fracture) [12,13], with 33% of non-repairable fractures in f_0 against 53% at f_1 [38].

An *in vitro* fracture resistance and fatigue study of endodontically treated teeth restored with fiber-reinforced or metallic posts reported that most of the cracks initiated at the same location as indicated in this study by $\sigma_{MC\ ratio}$ and fatigue analysis [36]. They evaluated teeth with ferule but their results resemble our non-ferule groups. This may be caused by the crown fracture that occurred in the *in vitro* test, leading to a condition in which a ferule no longer stabilizes the crown, providing a behavior more comparable to the non-ferule situation.

The fatigue analysis indicated damage in dentin after the planned number of cycles, with possible crack initiation. However, the simulated fatigue analysis did not create actual crack propagation, which is more complex to achieve. The *in vitro* results after fatigue tests presented 36% reduction in mean fracture strength for teeth restored with fiber post and a 16% reduction for metallic cast post-and-core [36]. In this study less fatigue damage was predicted in dentin in the MP group (higher SF, **Figure 9**) than other groups. The analysis of static and fatigue results supports that intra-radicular posts with higher elastic modulus provide higher fracture strength and accumulate less damage in fatigue tests [39]. In general, the f_1 models had lower $\sigma_{MC\ ratio}$ than f_0 models and lower bond failure risk. A systematic review indicated success/survival rates ranging from 0% to 97% in teeth restored without ferule and 66.7% to 100% with ferule [39].

Designs of clinical and experimental fracture resistance studies vary in the literature, making direct comparisons a challenge. Test parameters such as tooth dimensions, amount of tooth structure, presence of crown, material of crown, and distance between crown margins and the level of the base supporting the specimens all will influence the results [36]. Moreover, the simulation from intact bonds to complete bond failure was a simplification of actual failure processes. Nevertheless, the discussed comparisons with *in vitro* and clinical observations confirm that modeling frictional contact instead of perfect bonding can make a critical difference in the validity of FEA interpretations, and therefore our hypothesis was accepted.

Validated finite element analysis is a powerful tool for improving our understanding of stress conditions. The Introduction mentioned that the literature reports similar or lower stresses in tooth structures restored with GP compared to MP, but lower tooth strengths *in vitro* [1,9–11]. Simulation of bond failure turns out to be essential to explain such observations because stresses in intra-radicular restorations are highly influenced by interfacial conditions, showing that when the bond fails, the GP restoration generates higher stress levels in the tooth structure, whereas a lower incidence of catastrophic failures can be expected from the lower fracture strength of GP compared to MP.

5. Conclusion

Based on the present analysis, it was concluded that:

- Simulation of perfectly bonded intra-radicular posts did not closely match published experimental failure data;
- Simulation of complete bond failure had a better correlation with experimental data and is recommended for evaluating bonded intra-radicular posts in finite element analyses.

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References

[1] Zhou L, Wang Q. Comparison of Fracture Resistance between Cast Posts and Fiber Posts: A Meta-analysis of Literature. J Endod 2013;39:11–5. doi:10.1016/j.joen.2012.09.026.

[2] Naumann M, Sterzenbach G, Dietrich T, Bitter K, Frankenberger R, von Stein-Lausnitz M. Dentin-like versus Rigid Endodontic Post: 11-year Randomized Controlled Pilot Trial on No-wall to 2-wall Defects. J Endod 2017;43:1770–5. doi:10.1016/j.joen.2017.06.030.

[3] Barfeie A, Thomas MBM, Watts A, Rees J. Failure Mechanisms of Fibre Posts: A Literature Review. Eur J Prosthodont Restor Dent 2015;23:P115-27.

[4] Schmitter M, Sterzenbach G, Faggion CM, Krastl G. A flood tide of systematic reviews on endodontic posts: methodological assessment using of R-AMSTAR. Clin Oral Investig 2013;17:1287–94. doi:10.1007/s00784-013-0945-z.

[5] Theodosopoulou JN, Chochlidakis KM. A Systematic Review of Dowel (Post) and Core Materials and Systems. J Prosthodont 2009;18:464–72. doi:10.1111/j.1532-849X.2009.00472.x.

[6] Figueiredo FED, Martins-Filho PRS, Faria-e-Silva AL. Do Metal Post–retained Restorations Result in More Root Fractures than Fiber Post–retained Restorations? A Systematic Review and Meta-analysis. J Endod 2015;41:309–16. doi:10.1016/j.joen.2014.10.006.

[7] Sorrentino R, Di Mauro MI, Ferrari M, Leone R, Zarone F. Complications of endodontically treated teeth restored with fiber posts and single crowns or fixed dental prostheses—a systematic review. Clin Oral Investig 2016;20:1449–57. doi:10.1007/s00784-016-1919-8.

[8] Bolla M, Muller-Bolla M, Borg C, Lupi-Pegurier L, Laplanche O, Leforestier E. Root canal posts for the restoration of root filled teeth. In: Muller-Bolla M, editor. Cochrane Database Syst. Rev., Chichester, UK: John Wiley & Sons, Ltd; 2007. doi:10.1002/14651858.CD004623.pub2.

[9] De Castro Albuquerque R, De Abreu Polleto LT, Fontana RHBTS, Cimini CA.

Stress analysis of an upper central incisor restored with different posts. J Oral Rehabil 2003;30:936–43. doi:10.1046/j.1365-2842.2003.01154.x.

[10] Sorrentino R, Aversa R, Ferro V, Auriemma T, Zarone F, Ferrari M, et al. Three-dimensional finite element analysis of strain and stress distributions in endodontically treated maxillary central incisors restored with diferent post, core and crown materials. Dent Mater 2007;23:983–93. doi:10.1016/j.dental.2006.08.006.

[11] Madfa AA, Al-Hamzi MA, Al-Sanabani FA, Al-Qudaimi NH, Yue X-G. 3D FEA of cemented glass fiber and cast posts with various dental cements in a maxillary central incisor. Springerplus 2015;4:598. doi:10.1186/s40064-015-1345-4.

[12] Magne P, Lazari P, Carvalho M, Johnson T, Del Bel Cury A. Ferrule-Effect Dominates Over Use of a Fiber Post When Restoring Endodontically Treated Incisors: An In Vitro Study. Oper Dent 2017;42:396–406. doi:10.2341/16-243-L.

[13] Maroli A, Hoelcher KAL, Reginato VF, Spazzin AO, Caldas RA, Bacchi A. Biomechanical behavior of teeth without remaining coronal structure restored with different post designs and materials. Mater Sci Eng C 2017;76:839–44. doi:10.1016/j.msec.2017.03.152.

[14] Santos AFV, Meira JBC, Tanaka CB, Xavier TA, Ballester RY, Lima RG, et al. Can Fiber Posts Increase Root Stresses and Reduce Fracture? J Dent Res 2010;89:587–91. doi:10.1177/0022034510363382.

[15] Veríssimo C, Simamoto Júnior PC, Soares CJ, Noritomi PY, Santos-Filho PCF. Effect of the crown, post, and remaining coronal dentin on the biomechanical behavior of endodontically treated maxillary central incisors. J Prosthet Dent 2014;111:234–46. doi:10.1016/j.prosdent.2013.07.006.

[16] Santos AFV, Tanaka CB, Lima RG, Espósito COM, Ballester RY, Braga RR, et al. Vertical Root Fracture in Upper Premolars with Endodontic Posts: Finite Element Analysis. J Endod 2009;35:117–20. doi:10.1016/j.joen.2008.09.021.

[17] Schmitter M, Rammelsberg P, Lenz J, Scheuber S, Schweizerhof K, Rues S. Teeth restored using fiber-reinforced posts: In vitro fracture tests and finite

element analysis. Acta Biomater 2010;6:3747–54. doi:10.1016/j.actbio.2010.03.012.

[18] Rodríguez-Cervantes P-J, Sancho-Bru J-L, González-Lluch C, Pérez- González A, Barjau-Escribano A, Forner-Navarro L. Premolars restored with posts of different materials: fatigue analysis. Dent Mater J 2011;30:881–6. doi:10.4012/dmj.2011-098.

[19] Vasco MAA, Souza JTA de, Las Casas EB de, de Castro e Silva ALR, Hecke M. A method for constructing teeth and maxillary bone parametric model from clinical CT scans. Comput Methods Biomech Biomed Eng Imaging Vis 2015;3:117–22. doi:10.1080/21681163.2014.889579.

[20] Rees JS, Jacobsen PH, Hickman J. The elastic modulus of dentine determined by static and dynamic methods. Clin Mater 1994;17:11–5. doi:10.1016/0267-6605(94)90042-6.

[21] Santos-Filho PCF, Veríssimo C, Soares PV, Saltarelo RC, Soares CJ, Marcondes Martins LR. Influence of Ferrule, Post System, and Length on Biomechanical Behavior of Endodontically Treated Anterior Teeth. J Endod 2014;40:119–23. doi:10.1016/j.joen.2013.09.034.

[22] Holberg C, Winterhalder P, Rudzki-Janson I, Wichelhaus A. Finite element analysis of mono- and bicortical mini-implant stability. Eur J Orthod 2014;36:550–6. doi:10.1093/ejo/cjt023.

[23] Coelho CS de M, Biffi JCG, Silva GR da, Abrahão A, Campos RE, Soares CJ. Finite element analysis of weakened roots restored with composite resin and posts. Dent Mater J 2009;28:671–8. doi:10.4012/dmj.28.671.

[24] Albakry M, Guazzato M, Swain MV. Biaxial flexural strength, elastic moduli, and x-ray diffraction characterization of three pressable all-ceramic materials. J Prosthet Dent 2003;89:374–80. doi:10.1067/mpr.2003.42.

[25] Lanza A, Aversa R, Rengo S, Apicella D, Apicella A. 3D FEA of cemented steel, glass and carbon posts in a maxillary incisor. Dent Mater 2005;21:709–15. doi:10.1016/j.dental.2004.09.010.

[26] Krejci I, Mueller E, Lutz F. Effects of Thermocycling and Occlusal Force on

Adhesive Composite Crowns. J Dent Res 1994;73:1228–32. doi:10.1177/00220345940730061501.

[27] Miguez PA, Pereira PNR, Atsawasuwan P, Yamauchi M. Collagen Cross-linking and Ultimate Tensile Strength in Dentin. J Dent Res 2004;83:807–10. doi:10.1177/154405910408301014.

[28] Craig RG, Peyton FA. Elastic and Mechanical Properties of Human Dentin. J Dent Res 1958;37:710–8. doi:10.1177/00220345580370041801.

[29] Nalla RK, Imbeni V, Kinney JH, Staninec M, Marshall SJ, Ritchie RO. In vitro fatigue behavior of human dentin with implications for life prediction. J Biomed Mater Res 2003;66A:10–20. doi:10.1002/jbm.a.10553.

[30] Nalla RK, Kinney JH, Marshall SJ, Ritchie RO. On the in vitro Fatigue Behavior of Human Dentin: Effect of Mean Stress. J Dent Res 2004;83:211–5. doi:10.1177/154405910408300305.

[31] Norton RL. Machine Design: An Integrated Approach. 3rd ed. Pearson Prentice Hall; 2005.

[32] Duret B, Duret F, Reynaud M. Long-life physical property preservation and postendodontic rehabilitation with the Composipost. Compend Contin Educ Dent Suppl 1996:S50-6.

[33] Cormier CJ, Burns DR, Moon P. In vitro comparison of the fracture resistance and failure mode of fiber, ceramic, and conventional post systems at various stages of restoration. J Prosthodont 2001;10:26–36.

[34] Dietschi D, Romelli M, Goretti A. Evaluation of post and cores in the laboratory: rationale for developing a fatigue test and preliminary results. Compend Contin Educ Dent Suppl 1996:S65-73.

[35] Freedman G. The carbon fibre post: metal-free, post-endodontic rehabilitation. Oral Health 1996;86:23–6, 29–30.

[36] A. Alharbi F, Nathanson D, Morgano SM, Baba NZ. Fracture resistance and failure mode of fatigued endodontically treated teeth restored with fiber-reinforced resin posts and metallic posts in vitro. Dent Traumatol 2014;30:317–25. doi:10.1111/edt.12095.

[37] Hayes A, Duvall N, Wajdowicz M, Roberts H. Effect of Endocrown Pulp Chamber Extension Depth on Molar Fracture Resistance. Oper Dent 2017;42:327–34. doi:10.2341/16-097-L.

[38] Carvalho MA de. Avaliação da resistência à fadiga e modo de falha de coroas cerâmicas sem pino em incisivos sem férula tratados endodonticamente. Universidade Estadual de Campinas, 2017.

[39] Sarkis-Onofre R, Fergusson D, Cenci MS, Moher D, Pereira-Cenci T. Performance of Post-retained Single Crowns: A Systematic Review of Related Risk Factors. J Endod 2017;43:175–83. doi:10.1016/j.joen.2016.10.025.

3 CONCLUSÃO

Baseado no presente estudo, podemos sugerir que as análises por elementos finitos para pinos intracanais devem sempre considerar o uso de contatos friccionais pois apresentaram melhores similaridades com os dados experimentais disponíveis na literatura. Trabalhos realizados com simulação de contatos unidos devem ser avaliados com cautela.

REFERÊNCIAS*

A. Alharbi F, Nathanson D, Morgano SM, Baba NZ. Fracture resistance and failure mode of fatigued endodontically treated teeth restored with fiber-reinforced resin posts and metallic posts in vitro. Dent. Traumatol. 2014 Aug;30(4):317–25.

Akkayan B, Caniklioglu B. Resistance to fracture of crowned teeth restored with different post systems. Eur. J. Prosthodont. Restor. Dent. 1998 Mar;6(1):13–8.

Akkayan B, Gülmez T. Resistance to fracture of endodontically treated teeth restored with different post systems. J. Prosthet. Dent. 2002 Apr;87(4):431–7.

Butz F, Lennon AM, Heydecke G, Strub JR. Survival rate and fracture strength of endodontically treated maxillary incisors with moderate defects restored with different post-and-core systems: an in vitro study. Int. J. Prosthodont. 14(1):58–64.

De Castro Albuquerque R, De Abreu Polleto LT, Fontana RHBTS, Cimini CA. Stress analysis of an upper central incisor restored with different posts. J. Oral Rehabil. 2003 Sep;30(9):936–43.

Figueiredo FED, Martins-Filho PRS, Faria-e-Silva AL. Do Metal Post–retained Restorations Result in More Root Fractures than Fiber Post–retained Restorations? A Systematic Review and Meta-analysis. J. Endod. 2015 Mar;41(3):309–16.

Hayes A, Duvall N, Wajdowicz M, Roberts H. Effect of Endocrown Pulp Chamber Extension Depth on Molar Fracture Resistance. Oper Dent. 2017;42:327–34.

Madfa AA, Al-Hamzi MA, Al-Sanabani FA, Al-Qudaimi NH, Yue X-G. 3D FEA of cemented glass fiber and cast posts with various dental cements in a maxillary central incisor. Springerplus. Springer International Publishing; 2015;4(1):598.

* De acordo com as normas da UNICAMP/FOP, baseadas na padronização do International Committee of Medical Journal Editors - Vancouver Group. Abreviatura dos periódicos em conformidade com o PubMed.

Magne P, Lazari P, Carvalho M, Johnson T, Del Bel Cury A. Ferrule-Effect Dominates Over Use of a Fiber Post When Restoring Endodontically Treated Incisors: An In Vitro Study. Oper. Dent. 2017 Jul;42(4):396–406.

Maroli A, Hoelcher KAL, Reginato VF, Spazzin AO, Caldas RA, Bacchi A. Biomechanical behavior of teeth without remaining coronal structure restored with different post designs and materials. Mater. Sci. Eng. C. Elsevier B.V.; 2017 Jul;76:839–44.

Martínez-Insua A, da Silva L, Rilo B, Santana U. Comparison of the fracture resistances of pulpless teeth restored with a cast post and core or carbon-fiber post with a composite core. J. Prosthet. Dent. 1998 Nov;80(5):527–32.

Rodríguez-Cervantes P-J, Sancho-Bru J-L, González-Lluch C, Pérez- González A, Barjau-Escribano A, Forner-Navarro L. Premolars restored with posts of different materials: fatigue analysis. Dent. Mater. J. 2011;30(6):881–6.

Santos-Filho PCF, Veríssimo C, Soares PV, Saltarelo RC, Soares CJ, Marcondes Martins LR. Influence of Ferrule, Post System, and Length on Biomechanical Behavior of Endodontically Treated Anterior Teeth. J. Endod. 2014 Jan;40(1):119–23.

Santos AFV, Meira JBC, Tanaka CB, Xavier TA, Ballester RY, Lima RG, et al. Can Fiber Posts Increase Root Stresses and Reduce Fracture? J. Dent. Res. 2010 Jun 26;89(6):587–91.

Santos AFV, Tanaka CB, Lima RG, Espósito COM, Ballester RY, Braga RR, et al. Vertical Root Fracture in Upper Premolars with Endodontic Posts: Finite Element Analysis. J. Endod. American Association of Endodontists; 2009 Jan;35(1):117–20.

Schmitter M, Rammelsberg P, Lenz J, Scheuber S, Schweizerhof K, Rues S. Teeth restored using fiber-reinforced posts: In vitro fracture tests and finite element analysis. Acta Biomater. Acta Materialia Inc.; 2010 Sep;6(9):3747–54.

Sidoli GE, King PA, Setchell DJ. An in vitro evaluation of a carbon fiber-based post and core system. J. Prosthet. Dent. 1997 Jul;78(1):5–9.

Sirimai S, Riis DN, Morgano SM. An in vitro study of the fracture resistance and the incidence ofvertical root fracture of pulpless teeth restored with six post-and-coresystems. J. Prosthet. Dent. 1999 Mar;81(3):262–9.

Sorrentino R, Aversa R, Ferro V, Auriemma T, Zarone F, Ferrari M, et al. Three-dimensional finite element analysis of strain and stress distributions in endodontically treated maxillary central incisors restored with diferent post, core and crown materials. Dent. Mater. 2007 Aug;23(8):983–93.

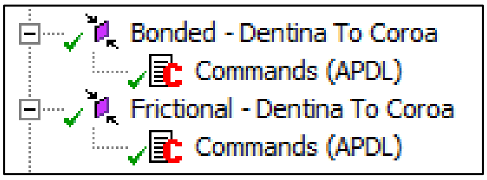
Veríssimo C, Simamoto Júnior PC, Soares CJ, Noritomi PY, Santos-Filho PCF. Effect of the crown, post, and remaining coronal dentin on the biomechanical behavior of endodontically treated maxillary central incisors. J. Prosthet. Dent. 2014 Mar;111(3):234–46.

Zhou L, Wang Q. Comparison of Fracture Resistance between Cast Posts and Fiber Posts: A Meta-analysis of Literature. J. Endod. Elsevier Ltd; 2013 Jan;39(1):11–5.

APÊNDICE 1 – CONFIGURAÇÃO *EKILL*

Estão apresentados abaixo os comandos utilizados para a execução do comando *ekill* e *ealive* dos contatos. Os textos inseridos seguintes a uma exclamação (!) nos comandos são observações, não sendo considerados na sua execução.

Primeiramente, cada par de contatos teve a opção de linhas de comando *Commands (APDL)* adicionado para identificação:



Dentro da opção *Commands (APDL)*, cada par de contatos teve uma identificação própria seguindo a lógica do texto abaixo:

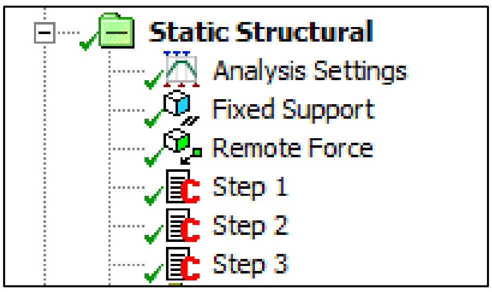
```
!Para especificar Contact "Contact"=cid
!Para especificar Target "Target"=tid

!Par de contatos bonded
contact_bonded=cid
target_bonded=tid
```

```
!Para especificar Contact "Contact"=cid
!Para especificar Target "Target"=tid

!Par de contatos fricctional
contact_fric=cid
target_fric=tid
```

Em seguida, com todos os pares de contatos identificados, uma opção de linha de comando foi adicionada para cada *step* na aba *Static Structural.*



Dentro da opção *Commands (APDL)* de cada *step* a execução foi configurada seguindo a lógica do texto abaixo:

```
!Especificar Full Newton-Rapson
nropt,full

!Selecionar os contatos a serem desativados
esel,s,type,,contact_bonded
esel,a,type,,target_bonded

!Desativar contatos selecionados
ekill,all

!Selecionar os contatos a serem ativados
esel,s,type,,contact_fric
esel,a,type,,target_fric

!Ativar contatos selecionados
ealive,all

!Selecionar tudo
allsel
```

O texto foi adaptado em cada *step* para satisfazer os pares de contatos que deveriam ser ativados ou desativados.

ANEXOS

Anexo 1 – Publicação em periódico

Artigo publicacado em periódico.

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Should adhesive debonding be simulated for intra-radicular post stress analyses?

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ABSTRACT

Objective. Elucidate the influence of debonding on stress distribution and maximum stresses for intra-radicular restorations.
Methods. Five intra-radicular restorations were analyzed by finite element analysis (FEA): MP = metallic cast post core; GP = glass fiber post core; PP = pre-fabricated metallic post core; RE = resin endocrowns; CE = single piece ceramic endocrown. Two cervical preparations were considered: no ferule (f_0) and 2 mm ferule (f_1). The simulation was conducted in three steps: (1) intact bonds at all contacts; (2) bond failure between crown and tooth; (3) bond failure among tooth, post and crown interfaces. Contact friction and separation between interfaces was modeled where bond failure occurred. Mohr–Coulomb stress ratios ($\sigma_{MC\ ratio}$) and fatigue safety factors (SF) for dentin structure were compared with published strength values, fatigue life, and fracture patterns of teeth with intra-radicular restorations.
Results. The $\sigma_{MC\ ratio}$ showed no differences among models at first step. The second step increased $\sigma_{MC\ ratio}$ at the ferule compared to step 1. At the third step, the $\sigma_{MC\ ratio}$ and SF for f_0 models were highly influenced by post material. CE and RE models had the highest values for $\sigma_{MC\ ratio}$ and lower SF. MP had the lowest $\sigma_{MC\ ratio}$ and higher SF. The f_1 models showed no relevant differences among them at the third step.
Significance. FEA most closely predicted failure performance of intra-radicular posts when frictional contact was modeled. Results of analyses where all interfaces are assumed to be perfectly bonded should be considered with caution.

1. Introduction

Computational stress analyses of intra-radicular restorations sometimes seem to contradict in vitro and clinical studies. A meta-analysis of *in vitro* studies evaluating roots restored with metal or fiber posts showed higher fracture strengths with metal posts [1]. However, several clinical systematic reviews that compared intra-radicular restorations showed inconclusive or contradictory results [2–8]. Some finite element analyses (FEA) showed lower stress values for fiber post restorations while others have suggested similar stress values regardless of post material [9–11]. Fracture patterns observed

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