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Mechanical performance of endodontic restorations with prefabricated posts. Sensitivity analysis of parameters with a 3D finite element model.

Many works have studied the effect of different parameters of the endodontically-restored tooth on its final strength, using in vitro tests and model simulations. However, the differences in the experimental set-up or modelling conditions and the limited number of parameters studied in each case prevent us from obtaining clear conclusions about the relative importance of each parameter. In this work, a validated 3D biomechanical model of the restored tooth was used for an exhaustive sensitivity analysis. The individual influence of twenty different parameters on the mechanical performance of an endodontic restoration with prefabricated posts was studied. The results bring up the remarkable importance of the loading angle on the final restoration strength. Flexural loads are more critical than compressive or tensile loads. Young's modulus of the post, as well as its length and diameter are the most influential parameters for strength, while others such as ferrule geometry or core and crown characteristics are less significant.

Keywords: prefabricated posts; finite element model; sensitivity analysis

1. Introduction

Prefabricated posts are often required to restore endodontically treated teeth. They provide retention and resistance for the core material of the restoration and also coronoradicular stabilisation (Robbins 1990). They are increasingly used to the detriment of cast posts, because the whole restoration can be performed in one visit, resulting in an easier and less expensive technique. Many different posts models are commercially available, and year after year manufacturers launch new post models onto the market, together with new core and cement materials aimed at improving the

existing ones. This makes difficult choosing the appropriate post, core and cement, which is crucial for a successful outcome of restoration procedure (Monticelli 2008; Stockton 1999). In this sense, it would be desirable for the clinician to know the effect that the different parameters in a tooth restoration with a prefabricated post have on the subsequent mechanical performance (retention and flexural strength) of the restoration.

We can find in the literature a high number of works that have tried to investigate this effect for some of the post design parameters, such as the post material, length, diameter and longitudinal shape (Balbosh and Kern 2006; Cooney, Caputo, Trabert 1986; Felton and others 1991; Kurer, Combe, Grant 1977; Miller 1982; Nergiz and others 1997; Ruemping, Lund, Schnell 1979; Standlee and others 1972; Standlee and Caputo 1992), achieving in some cases contradictory results. The effect of other post design parameters, such as the head shape, has been scarcely studied (Chang and Millstein 1993; Zalkind and others 2000), and hence provided no conclusive results. Other parameters of the restored tooth are not related to the post design, such as the ferrule height or the cement material, among others. There are few works in the literature that have investigated the effect of the ferrule height on the mechanical performance of the restoration (al-Hazaimeh and Gutteridge 2001; Stankiewicz and Wilson 2002), bringing, furthermore, contradictory results. Retention strength using different cements between the post and the root has been studied by several works (Bergeron and others 2001; Chan, Harcourt, Brockhurst 1993; Gallo and others 2002; Hauman, Chandler, Purton 2003; Lanza and others 2005; Mendoza and others 1997; Nissan, Dmitry, Assif 2001; Prisco and others 2003; Standlee, Caputo, Hanson 1978), but there are no studies dealing with the influence of cement thickness between the post and the root and between the core and the crown on the retention and flexural strength of the restoration.

Two different methodologies can be used to study the effect of the parameters of the restoration on its mechanical performance: in vitro experiments and simulations using finite element models (FEM). In vitro studies have two important drawbacks: their results are very dependent on many parameters that are hardly controllable (teeth dimensions, operator, procedure, etc.) and the limited number of specimens that can be prepared and tested restraints the number of design factors that can be included in the experimental design. As a consequence, results from these studies may provide misleading conclusions. For example, some in vitro studies have concluded that restorations with metallic posts are stronger than those with composite fibre posts (Martinez-Insua and others 1998; Sidoli, King, Setchell 1997); others have not observed significant differences (Hu and others 2003; Raygot, Chai, Jameson 2001) and others have found a greater strength of the restoration for fibre posts versus metallic posts (Akkayan and Gulmez 2002; Barjau-Escribano and others 2006; González-Lluch and others 2009; Isidor, Odman, Brondum 1996).

Biomechanical analysis of the restored tooth using FEM are increasingly used in recent years (Barjau-Escribano and others 2006; Boschian Pest and others 2006; Davy, Dilley, Krejci 1981; Genovese, Lamberti, Pappalettere 2005; González-Lluch and others 2009; González-Lluch and others 2011; Pegoretti and others 2002; Rodríguez-Cervantes and others 2007; Yaman, Karacaer, Sahin 2004). They allow a highly controlled analysis of one or several specific parameters on a single tooth model, resulting in a better comprehension of either the individual effect of a parameter or that combining different parameters. Moreover, they are faster and cheaper than in vitro experimentation, and eliminate the ethical implications related with the collection of real teeth specimens. Of course, the clinical application of the FEM results is conditioned by the accuracy of the model and its previous validation based on

experimental data. Another important concern when using FEM is the adequate interpretation of the results of the model: stresses resulting from the simulation are compared with the admissible stress limits of the different restoration materials, using some of the failure criteria found in the literature. Von Mises failure criterion is usual in most of the papers (Asmussen, Peutzfeldt, Sahafi 2005; Boschian Pest and others 2006; Hsu and others 2009; Pegoretti and others 2002; Sorrentino and others 2007), but this criterion is only valid for ductile materials with equal compressive and tensile strengths, which is not the case of many restorative materials that exhibit brittle behaviour such as ceramics, cements or resin composites (Christensen 2006; De Groot and others 1987; Pérez-González, Iserte-Vilar, González-Lluch 2011).

It is the aim of this work to present the results of a detailed sensitivity analysis of the individual influence of the parameters of an endodontic restoration with prefabricated posts on the mechanical strength of the whole restoration. To achieve this objective, a previously validated 3D finite element model of the restored tooth was used (Barjau-Escribano and others 2006; González-Lluch and others 2009; Rodriguez-Cervantes and others 2010; Rodríguez-Cervantes and others 2007), in which nineteen important restoration parameters (material properties of post, cement and core and geometrical parameters of the restoration components) together with the loading angle, were varied separately in a controlled way. Special care was taken in the selection of the failure criterion for comparing the stresses with the admissible stress limits of the different materials of the restoration. The novel failure criterion proposed by Christensen (Christensen 2006; Pérez-González, Iserte-Vilar, González-Lluch 2011) was used, which is valid for both ductile and brittle materials.

2. Materials and methods

A 3D FEM of a maxillary central incisor restored tooth was used for the study. This model was properly validated in previous works (Barjau-Escribano and others 2006; González-Lluch and others 2009; Rodríguez-Cervantes and others 2007).

The model was defined based on the geometry of a real maxillary central incisor obtained by means of a 3D scanner (main dimensions in Table 1). The endodontic treatment of the tooth and its later restoration with a prefabricated post was simulated by using the 3D modelling software Pro/Engineer (PTC, Needham, MA, USA). This software was used to generate, and later assemble the geometries for all the components. Figure 1 shows a sagittal section of the geometrical model, including all the components that were modelled, namely bone (cortical and trabecular components), periodontal ligament, root, gutta-percha, post, post-cement, core, crown and crown-cement. A thickness of 10 mm in the mesio-distal direction was considered for the bone.

A reference model was considered in order to study the effect of varying the different parameters of the restoration on its mechanical performance. This reference model simulated a real restoration with a simple cylindrical stainless steel post with a 1.5 mm diameter, cemented with Dual cement (Ivoclar Vivadent AG, Schaan, Liechtenstein), with a core made of dual cure resin ParaCore (Coltène/Whaledent Inc, Ohio, USA) and a final crown made of IPS Empress® (Ivoclar Vivadent AG, Schaan, Liechtenstein) and cemented with Dual Cement. The mechanical properties for all the component materials of this reference model were obtained from the literature and from the manufacturers (Table 2). The PDL has a non-linear response (Sorrentino and others 2009; Uddanwadiker, Padole, Arya 2007), but the differences in the stress distribution of a restored tooth using a linear or a non-linear model of the PDL have been found to be of less significance (Maceri, Martignoni, Vairo 2009). Dentine presents an

anisotropic behaviour, but the differences in the elastic modulus for the different directions are small (Ferrari and others 2008). Based on the above considerations, and in order to reduce the computation time, all materials were considered as linear and isotropic.

Twenty parameters of the reference model (Table 3) were selected to perform the sensitivity analyses: the five Young's moduli of restorative materials, and fourteen geometrical parameters of the restoration together with the loading angle, shown in Figure 2.

A set of possible values for each of the parameters was established (Table 4). Twenty sensitivity analyses were defined. In each of the analyses, one of the parameters was varied among the set of possible values, while the other parameters were kept at the reference value. Subsequently, a total of 96 different restoration configurations were considered.

A finite element model was defined for each of the 96 restoration configurations to be analysed. The Pro/Mechanica module, available within Pro/Engineer, was used to generate the finite element mesh, from the CAD geometry. Solid tetrahedral elements were used, with a mesh control for the maximal size of the elements of 0.3 mm on all the components, except on trabecular and cortical bone, where a maximal size of 1 mm was considered. The mesher included smaller elements in thin components as the cement, to maintain a reasonable value for the aspect ratio. The final models had almost 511,000 elements defined by approximately 88,000 nodes. The validity of the mesh was demonstrated by convergence tests. A load of 300 N was applied at an **A** angle to the radicular axis, as shown in Figure 2. As boundary conditions, the displacements of all nodes at the base of the cortical and trabecular bones were constrained, as well as the mesio-distal displacements of the nodes in the lateral sections of the bones.

All models were analyzed using MSC-Nastran (MSC Sofware Corp., Santa Ana, CA, USA), obtaining the stresses at each finite element. At each component, the stresses were compared with the tensile and compressive strengths of its material using the failure criterion proposed by Christensen (Christensen 2006; Pérez-González, Iserte-Vilar, González-Lluch 2011), calculating a 'cohesive safety factor' at each finite element (simple ratio that is intended to be greater than one, so that strength must be greater than stress). The Christensen criterion is valid for checking cohesive failure, but does not predict the possible adhesive failure between components bonded by the cement. In order to consider this failure mode for the finite elements of the cements, the maximum shear stress at each finite element was compared with the admissible shear stress of the bonding cement (half of the tensile strength of the cement), defining an 'adhesive safety factor'. The lowest of the cohesive and adhesive safety factors was considered as the safety factor at each finite element of the cements. To account for plasticity at specific zones of stress concentration, the 'component safety factor' was calculated at each component as the average of the safety factors at the finite elements of the component with safety factors below the 0.5 percentile. Finally, the 'overall safety factor' of the restored tooth was calculated as the lowest of the component safety factors.

In order to determine the influence of each of the parameters considered in the endodontic restoration, in each of the twenty analyses, the overall safety factors of the different models were compared with the overall safety factor of the reference model. The post-processing was performed with MSC-Patran (MSC Sofware Corp., Santa Ana, CA, USA) and Matlab program (MathWorks, Natick, MA, USA).

3. Results

Table 5 shows the results of the safety factors obtained in the reference model for each component. Post cement is the component with the lowest value (0.92) followed by the root (1.37). These components are, then, the most critical components in the endodontic restoration simulated with the reference model, and 0.92 is the overall safety factor of this simulation. Figure 3, shows a representation of the safety factors in three sections of the reference model (frontal, sagittal and transversal). White colouring represents areas with a safety factor greater than 10, and warmer colours represent lower safety factors. The post has not been displayed in this figure for the sake of clarity, as it presented high safety factors. This figure shows that the lowest safety factors appeared along the post cement and in the upper zone of the root, at the lingual aspect.

For each of the twenty analyses, the percentage of variation of the overall safety factor with respect to the reference case was calculated. The highest value for each analysis is presented in Figure 4. These results indicate that not all the parameters studied affect the mechanical performance of the endodontic restoration to the same extent. Only the variation of the parameters A, Epost, Dp1, Dp2, Lpr and Tp produced a percentage of variation higher than 10% (analyses 1, 2, 7, 8, 9 and 17). None of the parameters of the ferrule (Fh, Df1 and Df2) and the core (Hc, Dc1 and Dc2) produced a remarkable effect on the estimated mechanical performance of the endodontic restoration for the range of variation of the parameters considered in the study. With regard to Young's modulus of the materials, only that specific to the post component significantly affected the estimated resistance of the restoration, again for the range of variation of the moduli considered in the study.

For the parameters with percentage of variation of the safety factor higher than 10%, the percentage of variation of the overall safety factor versus the percentage of

variation of the parameters, always with respect to the reference model values, is shown in Figure 5.

The loading angle produced the most quantifiable effect (Figure 5). The overall safety factor increased by 66.1% and 235.9% respectively when the angle decreased to 25º and then to 0º, because of the reduced flexion component of the load. On the contrary, it decreased by 17.6% and 18.9% respectively when the angle increased to 75º and then to 90º, because of the increase of flexion. The best performance was observed for the case of a compressive load (0º), and the worst for the case of a flexural load (90º). For the case of retention (tensile load), the weakest component was the crown. In all other cases, post cement was the first component to fail such as in the reference model.

Young's modulus of the post was also an influential parameter. Figure 5 shows a 27.2% decrease of the safety factor when the modulus increased by 50% from its reference value. In these cases, the weakest component was always the post cement, as in the reference model (Figure 3). In contrast, the safety factor increased a 47.5% when the modulus decreased by 50% because of the absence of stress concentration in the post-cement interface, as can be seen in Figure 6 where the safety factor distribution for the case of the smallest modulus is presented (31 GPa). In fact, the weaker component was not the post cement but the root for the models with modulus equal or smaller than 104 GPa.

Apart from Young's modulus of the post, three other parameters of the post (Dp1, Dp2 and Lpr) also influenced the safety factor (Figure 5). When Dp1 was varied, the weakest component was always the post cement, and we observed an increasing tendency of the overall safety factor for smaller diameters of the post. A maximum increase of 27.5% was observed for a diameter decrease of 75%. When Dp2 was varied,

the weakest component was also the post cement in all cases. No clear tendency of the overall safety factor was observed in this case, but an optimum value was identified when the diameter Dp2 decreased by 25% with respect to the reference value. Finally, the overall safety factor increased as the length of the post (Lpr) shortened.

The safety factor increased by 47.1% when the length of the post decreased by 75%. Figure 7 shows the distribution of the overall safety factor for that case. With a shorter post, the root became the weakest component, instead of the post cement, as was the case for the reference model. This can be explained by the stress concentration reduction in the post cement interface.

No clear tendency was observed for the overall safety factor when varying the thickness of the post cement. An optimum value was identified for a thickness of 0.3mm (50% greater than the reference value). Notwithstanding this, only a slight influence was observed.

4. Discussion and conclusions

We have studied the separate effect of the parameters of an endodontic restoration with a prefabricated post on its mechanical performance by means of a 3D finite element model already validated in previous works. We have identified that, within the limitations of the study, the parameters that mostly influence the fracture resistance of the restoration are basically the parameters concerning the post selection (Young's modulus of its material, and diameter and length of the post), apart from the orientation of the load. A slight influence of the thickness of the post cement was also observed. The restoration has been found to be slightly sensitive to the parameters of the ferrule and the core, at least for the range of variation considered in the study for these parameters.

The strengths obtained in the works of the literature depend on the orientation of the load applied to the restored tooth. This orientation tries to simulate the different types of loads that appear during mastication (retention, flexion, etc.). The works in the literature use load angles, with respect to the radicular axis, that vary in the wide range from 30º to 60º for the case of simulating compressive-flexural forces during the mastication in the incisors (Al-Omiri and Al-Wahadni 2006; González-Lluch and others 2009; Ichim, Kuzmanovic, Love 2006; Lanza and others 2005; Sahafi and others 2005). Other works use 180º (tensile load) to test for retention during the simulation of chewing sticky food (Burns, Douglas, Moon 1993; Davy, Dilley, Krejci 1981; Genovese, Lamberti, Pappalettere 2005; Pegoretti and others 2002), and others 90º to simulate accidental loads (Davy, Dilley, Krejci 1981; Genovese, Lamberti, Pappalettere 2005; Pegoretti and others 2002). It is remarkable that no previous studies in the literature investigated the effect of different loading angles on the mechanical strength obtained. In our results we have observed better mechanical performance for compressive loads and a lower resistance as the flexion component of the load increases. This is in accordance with the comparison of experimental failure loads of the literature obtained under different load orientation (Milot and Stein 1992; Pérez-González and others 2012). The restoration seems to withstand better a compressive load than a tensile one. This last result cannot be validated with data from the literature, as the experimental loads measured in the retention tests available in the literature were obtained on specimens without the core and final crown on the post. The results of the work highlight the remarkable importance of the load orientation on the failure load expected for a restoration. The results set forth in the paper can serve as a guide when trying to compare the results of different works of the literature that were obtained using different load orientations.

A better mechanical performance has been observed when the Young's modulus of the post material decreases, which agrees with the literature ((Akkayan and Gulmez 2002; Barjau-Escribano and others 2006; Chuang and others 2010)). Mechanical resistance of the restoration seems to be favoured by thinner posts (at least for steel posts that were the ones considered in the simulations), which is also in accordance with the literature (Chuang and others 2010; Rodríguez-Cervantes and others 2007). Furthermore, shorter posts reduce the risk of failure (again, at least for steel posts), as it was experimentally obtained in a recent work (Chuang and others 2010).

The effect of the thickness of the cement in the post-dentine interface has been found to be moderate, with a reduction of the strength for the smallest thicknesses. The best results are obtained with thicknesses between 0.2 and 0.3 mm, while D'Arcangelo et al. (D'Arcangelo and others 2007) observed optimum performance for thicknesses between 0.1 and 0.3 mm. The results however are not comparable because they subjected the specimens to push-out loads, different to the compressive-flexural load used in our work. Anyway, the results are clinically relevant, because the thickness of the post cement is of difficult control by the dentist, and it has been found to not affect much the biomechanical performance of the restoration.

The failure modes associated with each of the models that have been analyzed can be estimated from the distributions of the safety factors estimated on the specimen. We can distinguish two different patterns. A first pattern is obtained for the reference model (Figure 3), with low safety factors concentrated along the post cement and in the upper zone of the root, at the lingual aspect, the cement post being the most critical component. In this case, a non-reparable vertical radicular failure is expected to occur, as reported in the literature (Akkayan and Gulmez 2002; Cormier, Burns, Moon 2001). For long stainless steel posts Chuang et al. (Chuang and others 2010) also found the

critical zone at the post neighbourhood. A second pattern corresponds to the case where the safety factors along the post cement increase and the cervical root turns out to be the most critical zone (e.g. Figures 6 and 7). In this case, a failure of the coronal part of the root is expected, which will result in more reparable failures. This is the case observed for posts with small Young's modulus, small diameter and short length, which has been reported in previous experimental works ((Akkayan and Gulmez 2002; Cormier, Burns, Moon 2001; González-Lluch and others 2009)). This change in the critical zone with the length of the steel post is also reported in a recent work (Chuang and others 2010), although they found the critical stresses at the vestibular side of the cervical root and we, in contrast, have found them at the lingual aspect. It is likely that the differences in the computation of the safety factor account for this difference. Chuang and others (2010) used von Mises equivalent stresses, which assume implicitly equal compressive and tensile strength for the material. But this assumption is not valid for dentine, which is more resistant under compressive stresses; that is why we have found the critical stresses at the lingual side, which is under tensile stresses and not in the vestibular side, which is under compressive stresses.

Joining all the results obtained in this work, we can venture to suggest some general recommendations for restoring teeth with prefabricated posts. It is desirable to use posts with a small Young's modulus (e.g. glass-fibre posts), as thin and short as possible and with some conicity. There are obviously some aspects not considered in this work that can modify or refine these recommendations. For example, in the simulations we haven't considered a hypothetical debonding of the core and crown from the root, which will probably make the post length play a more important role or even may lead to the recommendation for longer posts. Furthermore, we have not performed a detailed analysis of the cross influence of the parameters. It is possible that the effect

of varying a parameter separately may not have the same as the effect when combined with the variation of a second parameter. For example, a model combining the best value obtained for each of the parameters at a 50º loading angle was computed, and the overall safety factor obtained was 1.18, which is only 28% better than the reference model, whereas Fig. 5 shows that by changing only Young's modulus of the post provided, there was an improvement in strength of over 40%. A more detailed analysis of this crossed effect would require a factorial analysis including combined changes in selected parameters, and the authors are currently working on it.

The present study has some limitation, as it considers isotropic linear materials in the restoration. In recent years some works are introducing non-linear FEM to better represent the response of endodontic restorations, especially due to the non-linear response of the PDL (Sorrentino and others 2009; Uddanwadiker, Padole, Arya 2007). However, although the effect of excluding the ligament in the model has been demonstrated to induce important errors, the differences in stress distribution between a linear and non-linear model of the PDL are of less significance (Maceri, Martignoni, Vairo 2009). On the other hand, some materials of the restoration present anisotropic behaviour, such as dentine. In this sense, some recent works used orthotropic models for dentine (Ferrari and others 2008), but the differences in the elastic modulus for the different directions were small, and consequently this limitation probably do not affect to the conclusions of the present work.

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Table 1. Main dimensions of the modelled incisor.

Dimension		(mm)
Root length		14.4
Crown height		11.0
Mesio-distal diameter	at cemento-enamel junction (CEJ)	5.7
	at medial root height	4.7
Vestibulo-palatal diameter	at CEJ	7.1
	at medial root height	5.5

Table 2. Mechanical properties of the materials of the reference model

Material	Young's modulus E (GPa)	Poisson coefficient ν	Tensile strength (MPa)	Compressive strength (MPa)	References
Dentine	18.6	0.31	106	297	(Asmussen, Peutzfeldt, Sahafi 2005; Powers and Skaguchi 2006)
Gutta-percha	0.00069	0.45	15	15	(Asmussen, Peutzfeldt, Sahafi 2005; Friedman and others 1975)
Ligament	0.00125	0.45	2	2	(Asmussen, Peutzfeldt, Sahafi 2005; Komatsu 2010)
Cortical bone	13.7	0.30	120	180	(Asmussen, Peutzfeldt, Sahafi 2005; Burstein, Reilly, Martens 1976)
Trabecular bone	1.37	0.30	9	4	(Asmussen, Peutzfeldt, Sahafi 2005; Henriksen and others 2011)
Dual cement	10	0.30	106	242	Ivoclar Vivadent AG, Schaan, Liechtenstein, (Saskalauskaite, Tam, McComb 2008)
ParaCore	16.6	0.30	125	285	Coltène/Whaledent Inc, Ohio, USA, (Craig and Powers 2002)
IPS Empress®	62	0.30	160	162.9	Ivoclar Vivadent AG, Schaan, (Probster and others 1997)
Stainless steel	207	0.30	1436	1436	(Plotino and others 2007; Rodríguez-Cervantes and others 2007)

Table 3. Description of the parameters used for the sensitivity analyses.

Parameter	Description
E_{post}	Young's modulus of the post
E_{core}	Young's modulus of the core
$E_{post\ cement}$	Young's modulus of the post cement
E_{crown}	Young's modulus of the crown
$E_{crown\ cement}$	Young's modulus of the crown cement
A	Loading angle
Dp1	Diameter of the post at the radicular base
Dp2	Diameter of the post at the coronal height
Lpr	Length of the post inserted into the root (from the CEJ)
Lprc	Length of the cylindrical part of the post inserted into the root (from the CEJ)
Hpp	Height of the post protruding from the dentine
Fh	Ferrule height
Df1	Outer diameter of the ferrule at the CEJ
Df2	Outer diameter of the ferrule at the coronal height
Dhc	Diameter of the root canal for housing the post at the coronal height
Tc	Thickness of the crown cement
Tp	Thickness of the post cement
Dc1	Diameter of the core at the CEJ
Dc2	Diameter of the core at the coronal height
Hc	Height of the core

Table 4. Set of values for each parameter and analyses definition.

Analysis	Parameter varied	Reference value	Possible values
1	A	50 º	0º - 25º - 50º - 75º - 90º-180º
2	E_{post}	207 GPa	31 - 52 - 104 - 155 - 207 - 259 – 311
3	E_{core}	16.6 GPa	4.2 - 8.3 - 12.5 -16.6 - 24.9 - 33.2 - 41.5 - 49.8
4	$E_{post\ cement}$	10.0 GPa	2.5 - 5.0 - 7.5 - 10.0 - 15.0 - 20.0 - 25.0 - 30.0
5	E_{crown}	62.0 GPa	15.5 - 31.0 - 46.5 - 62.0 - 77.5 - 93.0 - 108.5 - 124.0 - 155.0 - 186.0
6	$E_{crown\ cement}$	10 GPa	2.5 - 5.0 - 7.5 - 10.0 - 12.5 - 15.0 - 17.5 - 20.0
7	Dp1	1.5 mm	0.38 - 0.75 - 1.13 - 1.50
8	Dp2	1.5 mm	0.75 - 1.12 - 1.50 - 1.88 - 2.25
9	Lpr	10 mm	2.5 - 5.0 - 7.5 - 10.0 -12.5
10	Lprc	0 mm	0.00 - 2.55 - 5.00 - 7.50
11	Hpp	3.5 mm	0.0 - 0.5 - 1.0 - 1.5 - 2.0 - 2.5 - 3.0 – 3.5
12	Fh	1.5 mm	0.00 - 0.75 - 1.13 - 1.50 - 1.88 - 2.25 - 2.63
13	Df1	3.0 mm	3.00 - 3.75 - 4.50
14	Df2 (Df2= Df1)	3.0 mm	2.10 - 2.25 - 3.00 - 3.75
15	Dhc	1.9 mm	1.90 - 2.38 - 2.86
16	Tc	0.10 mm	0.05 - 0.08 - 0.10 - 0.13 - 0.15 - 0.18
17	Tp	0.20 mm	0.10 - 0.15 - 0.20 - 0.25 - 0.30 - 0.35
18	Dc1	5.0 mm	5.0 - 5.13 - 5.25
19	Dc2	3.2 mm	1.6 - 2.4 - 3.2 - 4.0 - 4.8
20	Hc	5.0 mm	3.75 - 5.00 - 6.25

Table 5. Safety factor obtained at each component in the reference model ([*] indicates adhesive safety factor)

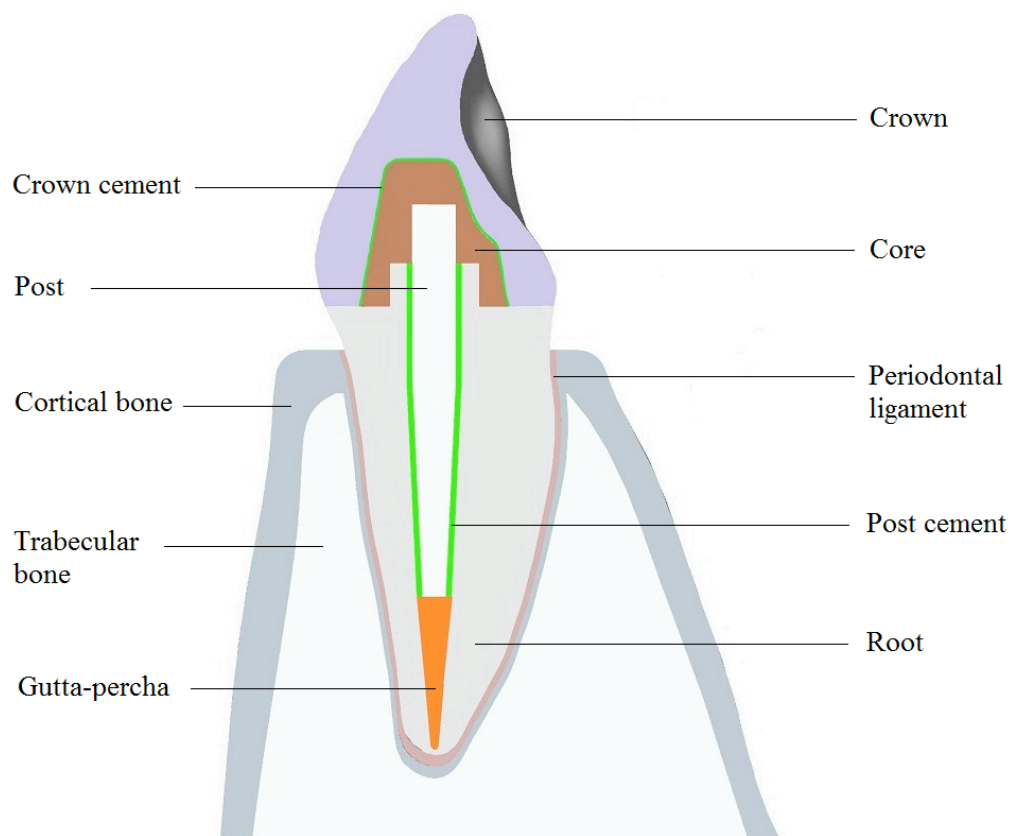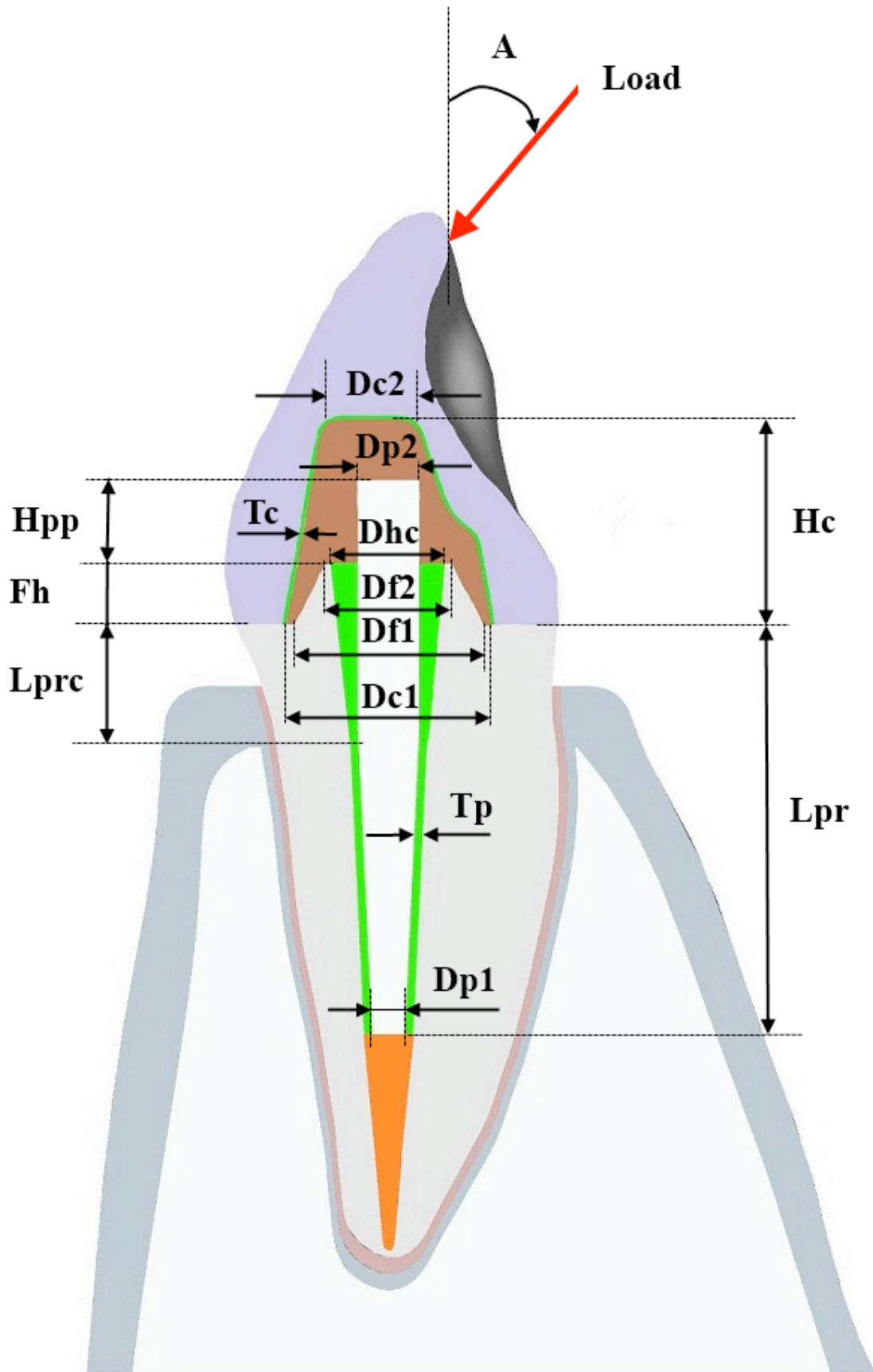| Component	Safety factor
Post cement	0.92[*]
Root	1.37
Crown	3.05
Post	8.12
Core	6.03
Crown cement	2.17[*]

Figure 1: Sagittal section of the geometrical model. Modelled components.

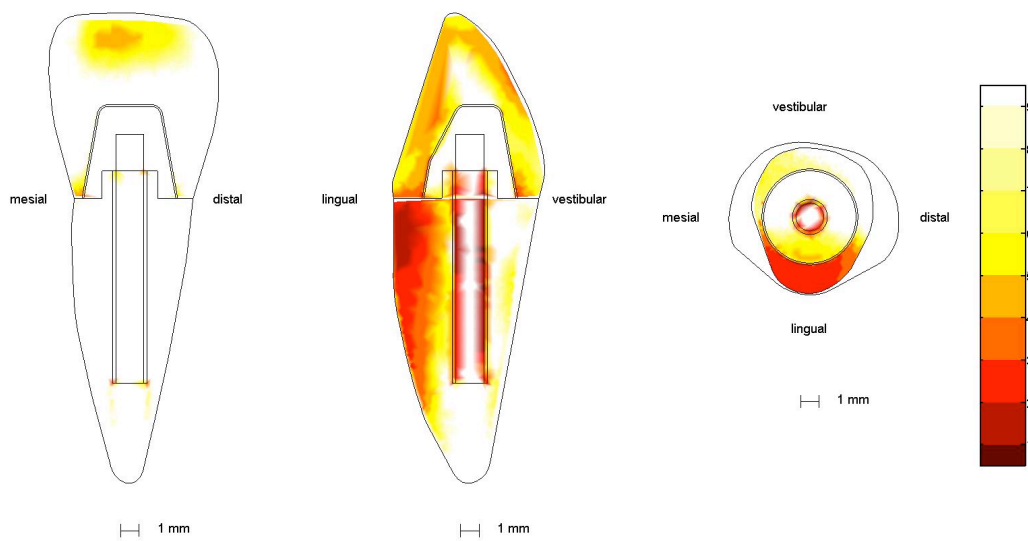Figure 2. Geometrical parameters of the restoration and loading angle, considered as parameters of the analysis.

Figure 3. Representation of the safety factors in the reference model (post not displayed).
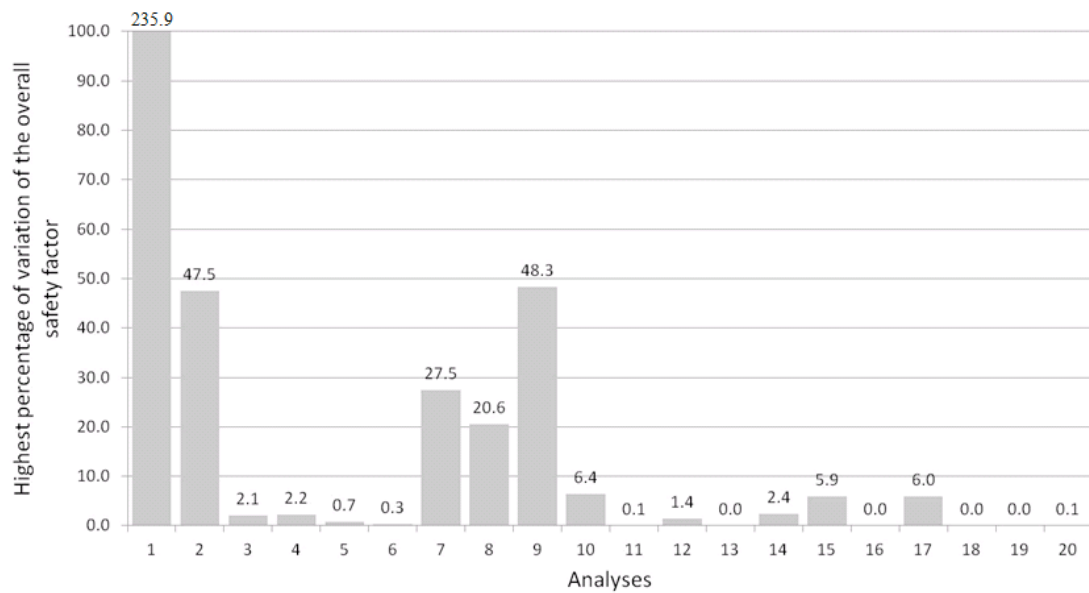
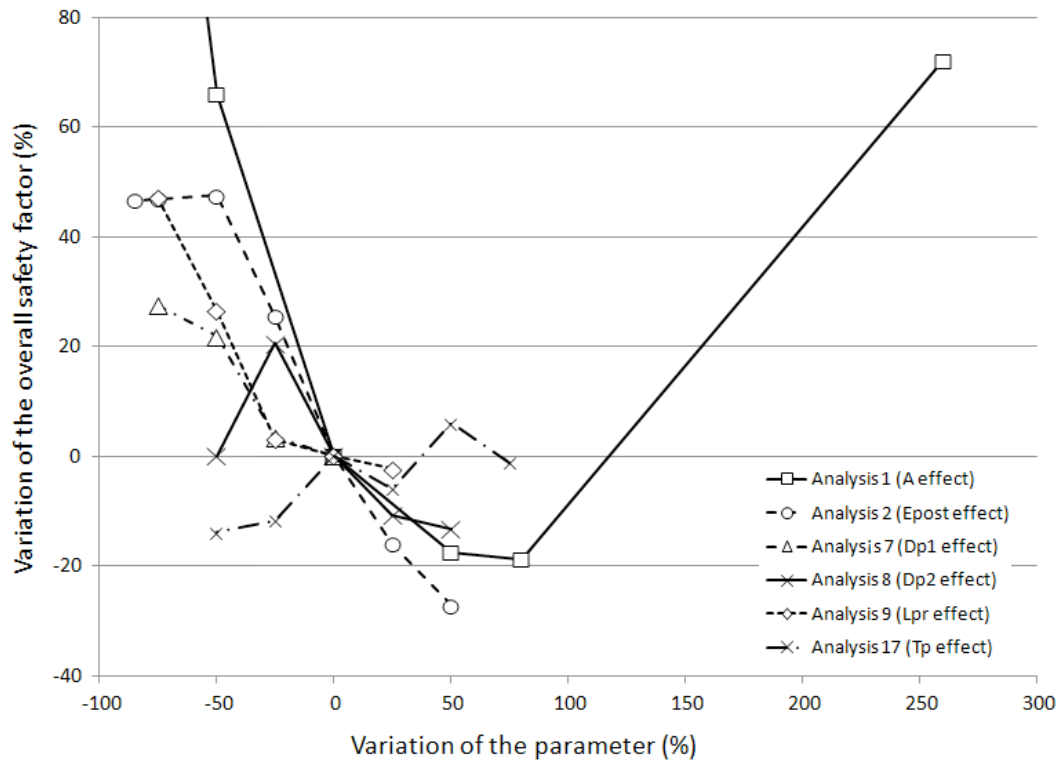Figure 4. Highest percentage of variation of the overall safety factor for each analysis

Figure 5. Results for analyses 1, 2, 7, 8, 9 and 17. Percentage of variation of the overall safety factor versus the percentage of variation of the parameter with respect to the reference values.
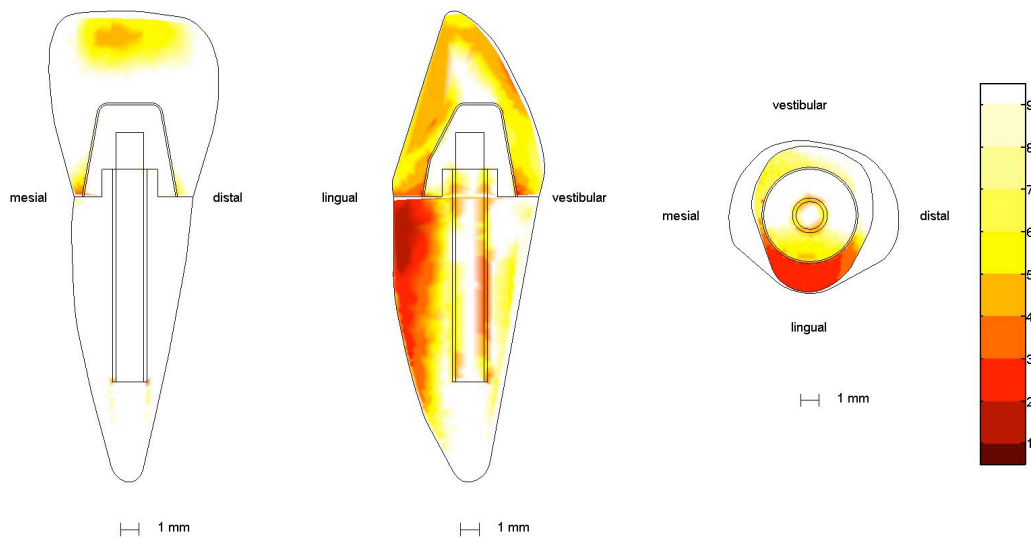

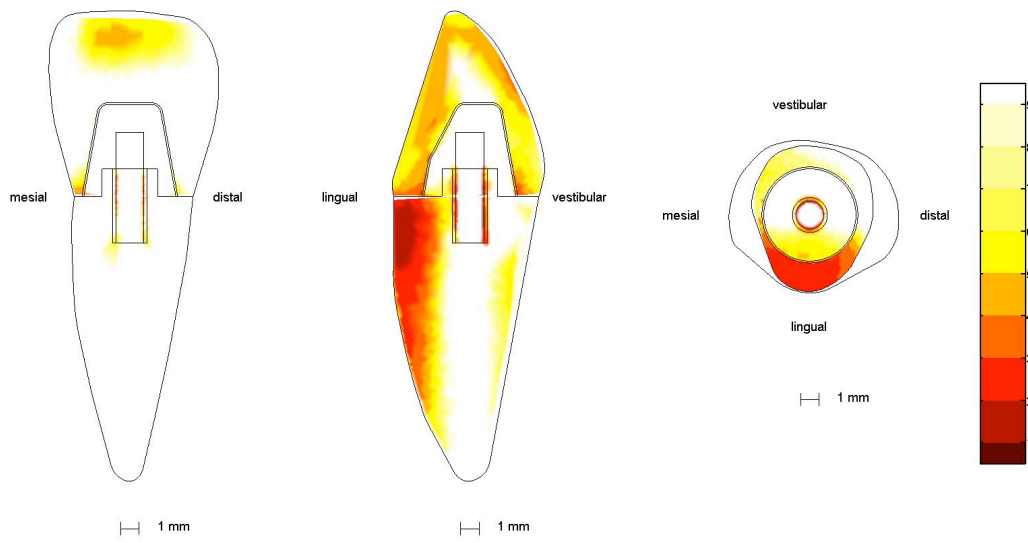Figure 6. Representation of the safety factors when Ep=31 GPa (post not displayed).

Figure 7. Representation of the safety factors when Lpr=2.5 mm (post not displayed).