Mechanical behaviour of endodontic restorations with multiple prefabricated posts: A finite-element approach

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Hoc libellum Mario Martignoni dicamus dum scribuntur paginae eheu nobis adempto

Abstract

This paper investigates some mechanical aspects of a new endodontic restoration technique, based on the idea that the root cavity can be more efficiently filled if multiple prefabricated composite posts (PCP) are employed. Multi-post technique increases bearing capacity and durability of endodontically treated teeth, as shown by numerical simulations performed through three-dimensional elastic finite-element static analyses of a lower premolar, constrained by a non-linearly elastic spring system representing the periodontal ligament, under several parafunctional loads. The influence of PCPs’ number, material and dimensions is investigated by comparison of the resulting stress fields with those obtained in cases of traditional restorations (cast metal post and cemented single-PCP) and natural tooth, highlighting the advantages of the proposed technique when standard restorative materials are considered. A risk-analysis of root-fracture and interface-failure shows that cast gold-alloy post produces high stress concentrations at post-dentin interface, whereas multi-post solution leads to a behaviour closer to the natural tooth’s, exhibiting some advantages with respect to single-PCP restorations. As a matter of fact, whenever PCPs’ overall cross-section area increases, multi-post solution induces a significant reduction of stress levels into the residual dentin (and therefore the root-fracture-risk decreases) as well as of the expected polymerization shrinkage effects. Moreover, interfacial stress values in multi-post restorations can be higher than the single-PCP ones when carbon-fibre posts are considered. Nevertheless, the interfacial adhesive/cohesive failure-risk is certainly acceptable if glass-fibre posts are employed. © 2007 Elsevier Ltd. All rights reserved.

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1. Introduction

Endodontic restoration represents a challenging task in the field of the oral rehabilitation practice and modern clinical trend consists in preserving teeth even if the endodontic treatment leaves a small amount of residual dentin. In endodontics, two types of post-and-core systems are usually adopted in order to rehabilitate a root canal and provide retention for crown: cast metal posts and prefabricated posts (commercially available in different geometries, dimensions and materials).

A cast metal post (e.g. gold-alloy post) is obtained on the basis of a mould taken directly from the root cavity (Baraban, 1967) and it can be either forced (frictioning post) or bonded by using a ligant. Both techniques require a big amount of preparatory work and can lead to the residual dentin being overstressed, causing root fracture and tooth losing, because of great stiffness in-homogeneity between metal and dentin, possible contact imperfections, eigenstresses originated by post’s setting.

For these reasons, post-reinforced systems based on a prefabricated composite post (PCP), generally cemented into the treated root and with the out-of-root part embedded into a composite core, are usually preferred. Many authors (e.g. Pegoretti et al., 2002) have shown that choosing a PCP’s material with stiffness close to the dentin’s, the restoration structure can better reproduce the natural load transmission mechanisms, reducing overs-tresses. This technique reduces the preparatory work but,
on the other hand, it can result critical when the treated root cavity is large and irregular. In this case, a single prefabricated post cannot exactly follow the shape of the cavity and a large amount of cement is needed to fill gaps between post and residual dentin. Accordingly, due to poor stiffness and strength of the usually adopted cements, important in-homogeneities are introduced into the restored structure. Moreover, significant polymerization shrinkage phenomena can arise, ranging from 1.5% to 6% of the total volume (Davidson and de Gee, 1984; de Gee et al., 1993; Davidson and Feilzer, 1997; Labella et al., 1999). As a consequence, adhesive and cohesive imperfections as well as self-equilibrated stress fields can be induced (Versluis et al., 2004; Kleverlaan and Feilzer, 2005), increasing the interfacial failure-risk and reducing the fatigue-life of the restoration. The magnitude of these self-equilibrated stress fields depends on the restorative composite (filler and matrix) and its mechanical characteristics as well as on cavity configuration (Braga and Ferracane, 2004). Therefore, in areas where shrinkage induces stresses higher than the composite-to-dental-substrate bond limit-strength, a gap will develop, increasing risk for post-operative sensitivity and recurrent caries (e.g. Brännström, 1984; Eick and Welch, 1986). A recent study demonstrates that the percentage of dentinal gaps in a composite in vivo restoration may vary between 14% and 54% of the total interface, depending on materials and techniques used (e.g. Hannig and Friedrichs, 2001). This occurrence, among others, can be naturally related to the high failure incidence (of about 35% on a mean time of about 6–7 years) experienced by Segerstrom et al. (2006) on traditional post-reinforced systems based on carbon-fibre PCP.

In authors’ opinion, when endodontic treatment leaves a wide and irregular root cavity, a solution overcoming these drawbacks and saving the advantages of the PCP-systems consists in using multiple commercial posts for the restoration. In this way, smaller quantities of filling cement and core-resin are required, smaller in-homogeneities are introduced, and a larger core-post interface is obtained. Accordingly, shrinkage effects are minimized (proportionally to the polymerization volumes reduction), the post pull-out risk is reduced, and a longer restoration durability to fatigue-cyclic loading and thermic conditions can be expected. Moreover, multi-post approach reduces the necessity of drilling dentin in order to adapt posts to root cavity, resulting in a better maintenance of the tooth structure. From a static point of view, as a steel-bar-reinforced concrete beam, a restoration based on several reinforcement posts centrifuged far from the tooth axis exhibits an increased bearing capacity with respect to intrusive/extrusive forces as well as to bending moments. These latter are induced by masticatory and pathologic loads with components in the occlusal plane.

From a clinical point of view and in comparison to the classical single-PCP treatment, the proposed technique has no inherent difficulties, apart from the lack of commercial availability of PCPs with reduced transversal dimensions. It has been successfully applied in the last two years by one of the authors in cases where the endodontic treatment had left a wide root cavity and up to today there is not any evidence of structural and/or clinical treatments’ failure. Only as an example and in the case of different patients and teeth, Fig. 1 shows some endodontic restorations performed through double- and triple-post use.

Since in vivo observations are difficult and time-consuming, numerical simulation represents an effective tool to compare performance of different restoration methodologies. Therefore, in this paper the proposed multiple-post restoration technique is analysed through a three-dimensional finite-element approach. Finite-element method has been widely used for dental applications in last

Fig. 1. Examples of clinical applications of the proposed restoration technique. Double-post (cases a and b) and triple-post restorations (case c): occlusal (above) and vestibular (below) views.
years. Bidimensional analyses are performed until today (e.g. Farah et al., 1973; Davy et al., 1981; Ko et al., 1992; Pegoretti et al., 2002; Toparli, 2003), whereas three-dimensional models of dental systems have been introduced in the 1990s (e.g. Ho et al., 1994; Holmes et al., 1996; Yaman et al., 1998; Joshi et al., 2001; Ausiello et al., 2002; Asmussen et al., 2005; Genovese et al., 2005; Lanza et al., 2005; Ichim et al., 2006) and are successfully validated by experimental tests and clinical observations.

With the aim to draw general conclusions, case studies are performed on single, double, and triple-PCP restorations of a lower premolar under several loads, considering different PCPs’ composite materials and geometries. According to values of physical constants, dynamical (shock, waves) and viscous effects are neglected and purely static analyses are worked out. Natural (e.g. dentin) and artificial (e.g. post, cement) material behaviour is assumed to be linearly elastic and perfect bonding between different materials is also assumed. To take into account tooth–bone interaction effects and in situ tooth’s conditions, a non-linear model of the periodontal ligament (PDL) is implemented, based on available experimental results. In order to reproduce accurately the three-dimensional geometries of both tooth and intervention regions, a parametric homemade modelling-code is employed. Comparisons with both cast gold-alloy restoration and natural healthy tooth are presented, highlighting the advantages of the new proposed technique.

2. Materials and methods

2.1. Numerical models and materials

In this paper a human lower premolar is analysed considering the following cases:

(i) natural healthy tooth;
(ii) pulpless tooth restored by a cast gold-alloy post;
(iii) pulpless tooth restored by a single PCP ($n_{PCP} = 1$);
(iv) pulpless tooth restored employing the multi-post technique, i.e. by using two ($n_{PCP} = 2$) or three ($n_{PCP} = 3$) prefabricated posts.

In order to analyse the influence of posts’ dimensions in multi-post applications, two restoration typologies are considered for the case (iv). In the first one (case OA), the overall post-cross-section area on a plane orthogonal to the tooth axis at the cervical zone is taken constant and equal to that one of the case (iii). In other words, the cross-section area of each post decreases when $n_{PCP}$ increases. In the second case (case SA), each post has the same cross-section area as case (iii); therefore, the overall post-cross-section area increases when $n_{PCP}$ increases. The residual-dentin thickness is assumed to be the same in all analysed restored-tooth models. Fig. 2 summarizes the treated cases, showing the employed intervention dimensions and relevant notations.

A three-dimensional CAD model of the tooth is generated by means of a parametric cubic-interpolation algorithm implemented through a MATLAB® homemade code. It is able to reproduce the solid model of endodontically treated teeth starting from pictures or X-ray images and assigning intervention and morphological parameters (Vairo, 2003).

User-assigned coordinates and shape parameters are identified by a comparison procedure based on the pictures/X-ray-images relevant to mesial-distal, buccal-lingual and occlusal views. By cubic interpolation on input data, significant primary profiles of the tooth are reproduced,
longitudinal (i.e. belonging to planes through the tooth axis z) for the crown and transversal ones (i.e. orthogonal to z) for the root. Afterwards, cubic-interpolated secondary profiles are created in planes at different angles around z for the crown and at different values of the z coordinate for the root. The outer wire-frame model is completed by adding dual profiles for both root and crown, i.e. transversal profiles on crown and longitudinal on root. In a next phase, using a similar parametric technique, the inner wire-frame model of the intervention regions (i.e. cavity, core build-up, post(s), gutta-percha region) is generated. The complete three-dimensional solid model is built up by fitting inner and outer profiles through a preprocessing tool whose output is fully compatible with the ANSYS® environment. The commercial tool ANSYS 7.1 is then used to obtain a discrete finite-element solid model and to analyse it. Three-dimensional meshes are created through 10-nodes tetrahedral elements with quadratic displacements shape functions and three degrees of freedom per node, with a mesh-size’s mean value of about 0.2 mm, resulting from an optimization process based on convergence analyses. Numerical models include about 130 000 elements and 185 000 nodes; continuity of displacement fields through material interfaces is imposed. Fig. 3 summarizes steps needed to generate a finite-element model.

In order to assess the effectiveness of the new technique with different PCP-materials, two cases are considered: composite carbon-fibre posts similar to Composipost® (Duret et al., 1990) and composite glass-fibre posts proposed by Pegoretti et al. (2002).

Under typical pathological and functional loads, dry-material models are usually employed and therefore fluid-solid interaction effects are neglected. All materials, except posts, are taken as linearly elastic and isotropic, whereas PCPs are modelled as transversally isotropic. Relevant elastic constants are summarized in Table 1. All constitutive parts of the (restored) tooth are taken as homogeneous.

2.2. Loads

Two loading cases are separately considered. The first consists in a vertical intrusive force of 400 N applied at the top of the tooth; the second one, in an oblique force of 200 N at the same point, angled at 45° with respect to the occlusal plane, and oriented towards the buccal side (see Fig. 2). According to a number of classical results, the vertical load value can be considered representative of the mean force relevant to the maximum biting state on a premolar region (e.g. Howell and Manly, 1948; Mansour and Reynik, 1975; Tortopidis et al., 1998; Bukke, 2006), whereas the oblique case reproduces parafunctional states related to bruxism (involuntary grinding and clenching) (e.g. Nishigawa et al., 2001; Lobbezoo et al., 2006) as well as to limit chewing conditions in the case (involuntary grinding and clenching) (e.g. Nishigawa et al., 2001; Lobbezoo et al., 2006). Others, consider ligament as an isotropic linearly elastic medium (e.g. Joshi et al., 2001; Pegoretti et al., 2002; Asmussen et al., 2005). In authors’ opinion and as it will be shown in the following, both assumptions produce unrealistic results. The first approach is clearly not able to reproduce stress and strain fields in the root region, because the imposed boundary condition induces vanishing strains around the boundary itself, opposite to the real behaviour of a tooth constrained by deformable PDL. Moreover, for the same reason, stress and strain fields in the cervical region obtained in the case of a fully constrained root boundary are very far from the real ones. On the other hand, due to the strong anisotropic and non-linear PDL-behaviour, isotropic linearly elastic models do not allow to determine the real displacement and stress fields (see Provaditis, 2000).

2.3. Constraints: the PDL model

In order to describe in a realistic way the tooth–bone interaction effects, the periodontal ligament (PDL) has to be suitably modelled. Many authors assume the restored tooth perfectly fixed at any boundary point belonging to PDL’s region (e.g. Ausiello et al., 2002; Genovese et al., 2005; Lanza et al., 2005). Others, consider ligament as an isotropic linearly elastic medium (e.g. Joshi et al., 2001; Pegoretti et al., 2002; Asmussen et al., 2005). In authors’ opinion and as it will be shown in the following, both assumptions produce unrealistic results. The first approach is clearly not able to reproduce stress and strain fields in the root region, because the imposed boundary condition induces vanishing strains around the boundary itself, opposite to the real behaviour of a tooth constrained by deformable PDL. Moreover, for the same reason, stress and strain fields in the cervical region obtained in the case of a fully constrained root boundary are very far from the real ones. On the other hand, due to the strong anisotropic and non-linear PDL-behaviour, isotropic linearly elastic models do not allow to determine the real displacement and stress fields (see Provaditis, 2000).

Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>E (GPa)</th>
<th>v</th>
<th>G (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dentin</td>
<td>18.6</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>Enamel</td>
<td>41.0</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>Pulp</td>
<td>0.98 x 10⁻³</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>Restored crown (ceramic)</td>
<td>380</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Adhesive layer crown-core</td>
<td>7.6</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>Cast metal post (ILOR56: gold-alloy post)</td>
<td>93.0</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Carbon-fibre posts</td>
<td>125.0 [8.5]</td>
<td>0.25 [0.32]</td>
<td>3.1 [3.0]</td>
</tr>
<tr>
<td>Glass-fibre posts</td>
<td>40.0 [11.0]</td>
<td>0.26 [0.32]</td>
<td>4.2 [4.1]</td>
</tr>
<tr>
<td>Gutta-percha</td>
<td>0.69 x 10⁻³</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>Filling cement</td>
<td>5.6</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Core composite resin</td>
<td>12.4</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

E and G indicate the Young’s and shear modulus, respectively (tangent moduli), whereas v is the Poisson’s ratio. Referring to composite fibre posts, the quantities in square brackets indicate properties evaluated in transverse-to-fibre direction.

1From Ko et al. (1992).
2From Pegoretti et al. (2002).
3From Tanaka et al. (2003).
4Alumina ceramic Procera; data provided by the manufacturer (Nobel Biocare, Gothenborg, Sweden).
5Variolink II + HelioBond; data provided by the manufacturer (Ivoclar Vivadent, Schaun, Liechtenstein).
6Relix Unicem; data provided by the manufacturer (3M ESPE AG, Seefeld, Germany).
7Clearfil F2; data provided by the manufacturer (Kuraray, Osaka, Japan).
A number of refined PDL models has been recently developed: Natali et al. (2002) propose a multi-phase formulation which takes into account the PDL’s fluid phase; Gei et al. (2002) analyse the PDL behaviour through an interface model, based on an ad hoc potential function; Provaditis (2000) analyses several anisotropic elastic and visco-elastic models, considering the different orientation of the PDL’s collagenous fibres. Nevertheless, although refined and complex PDL models are suitable for the analysis of the tooth mobility under orthodontic loads, i.e. under small forces and low loading rates, some approximations can be considered acceptable and advantageous from a computational point of view in the case of functional and pathological processes related to higher force values.

In this work, in view of a finite-element computational scheme, the PDL’s mechanical behaviour is directly described through an elastic anisotropic non-linear discrete model, in which all fluid and viscoelastic effects are disregarded. The PDL’s response to compression, tension and shear, is locally fitted through localized three-dimensional springs, connecting nodes on the PDL’s region (at the dentin’s external surface; see Fig. 2) to the cortical bone. Due to its high stiffness, this latter is assumed to be a rigid, fixed body. For each dentinal-PDL node a spring-chain constituted by eight linearly elastic elements is introduced. Each element acts both in normal-to-dentin and parallel-to-dentin directions, activating itself according to given elongation intervals, with stiffness depending on the local PDL’s thickness and elastic tangent modulus.

As far as stiffnesses in normal-to-dentin direction are concerned, the PDL’s thickness $t_{PDL}$ along the root axis is modelled through a quadratic least-square fit obtained from the experimental data of Toms et al. (2002), whereas tangent modulus is evaluated as the slope of a piecewise linear least-square fit of stress–strain experimental curves proposed by Nishihira et al. (2003). In detail (see Fig. 4) the high deformation rate response (250%/s) and the quasi-static one (0.005%/s) are considered as limits of the PDL’s behaviour. The first one is related to short-term loadings, whereas the second refers to orthodontic long-term processes. For both cases, the fitting rule guarantees that in the extreme intervals elastic moduli coincide with consolidated values available in literature (e.g. Goel et al., 1992; Ko et al., 1992; Rees and Jacobsen, 1997).

Parallel-to-dentin stiffnesses are computed by using the same thickness model and by assuming that shear reactions appear whenever the local shear strain $\gamma$ exceeds 0.25 rad. This assumption is consistent with the average behaviour experienced by Toms et al. (2002). Accordingly, local transverse stiffnesses are evaluated through the actual transverse elastic modulus $G_{PDL}$ defined as:

$$G_{PDL}(c, z) = \begin{cases} 0 & \text{if } \gamma \leq 0.25 \text{ rad}, \\ \max(G_{\text{min}}(c), G(c)) & \text{otherwise}, \end{cases}$$

where $G_{\text{min}}(c)$ represents the value of the transverse modulus obtained by the least square method, from the quadratic fit of the experimental data proposed by Toms et al. (2002) for pure shear tests (i.e. when $\varepsilon = 0$, $\varepsilon$ being the PDL strain along the direction orthogonal to the tooth’s surface); $G(c) = E_{PDL}(c)[2(1 + \nu_{PDL})^{-1}]$ is the shear modulus computed considering the actual longitudinal modulus $E_{PDL}(c)$ and assuming the PDL a nearly incompressible isotropic material, i.e. with the Poisson’s ratio $\nu_{PDL}$ equal to 0.45 (e.g. Pegoretti et al., 2002).

The PDL’s spring elements are generated and added to the finite-element models through an ad hoc preprocessing Fortran-code which takes as input some primary geometrical and topological data (i.e. nodal coordinates and elements belonging to the PDL’s region of the root’s outer boundary).

Due to the non-linearity of the PDL’s model, non-linear numerical analyses have to be performed, considering a large displacement finite-element formulation. The iterative process employs a modified Newton–Raphson approach, based on the arc-length method (Zienkiewicz and Taylor, 1998).

In order to assess the effectiveness of the proposed discrete approach, the PDL model has been validated considering the natural-tooth case, under intrusive and horizontal (i.e. in the occlusal plane and oriented towards the buccal side) forces applied at the top of the crown, and a quasi-static PDL response (i.e. an orthodontic behaviour).

The PDL has been discretized through about 18 000 spring-chains. Fig. 4b shows the obtained results in comparison with some experimental results on tooth mobility (Muhlemann, 1960; Picton, 1964; Brunski, 1992; Hinterkausen et al., 1998) in the case of a quasi-static PDL behaviour (strain rate: 0.005%/s).

![Fig. 4. Non-linear model of the periodontal ligament. (a) Experimental data and fitting results employed for setting the model (*): Goel et al., 1992; (+): Ko et al., 1992; (•): Picton, 1963; (■): Brunski, 1992; Present PDL model (0.005 %/s)); (b) validation: comparisons with some experimental results on tooth mobility (Muhlemann, 1960; Picton, 1964; Brunski, 1992; Hinterkausen et al., 1998) in the case of a quasi-static PDL behaviour (strain rate: 0.005%/s).](Image)
Results proposed by Picton (1964) and Hinterkausen et al. (1998) refer to average values measured on first lower premolars, whereas those given by Brunsli (1992) and Muhlemann (1960) concern a first maxillary molar and an average displacement value on several teeth, respectively. Taking into account the in-homogeneity of the employed experimental data for setting and validating the model, and considering that they refer to tooth mobility under orthodontic loads, a satisfactory agreement can be stated.

On the other hand, the load intensity here considered for the statical simulations (see Section 2.2), frequently—but not always (e.g. Nishigawa et al., 2001)—related to events with a properly impulsive character, suggests, in order to investigate the effectiveness of the proposed restoration technique under parafunctional loads, a PDL model based on a short-term-loading response. Nevertheless, as it will be proved through some results given in the following, PDL model based on a quasi-static response produces stress distributions with higher peaks than the short-term one. Accordingly, with the aim to compare quantitatively the maximum bearing-capacity produced by different restoration techniques, the discrete PDL model based on a quasi-static approach results more conservative from an engineering point of view.

2.4. Stress measures

Results obtained through finite-element analyses are post-processed in order to evaluate several stress measures: Von Mises equivalent stress \( \sigma_{VM} \), Rankine equivalent stresses \( \sigma_{R1}, \sigma_{R2} \) and shear stress modulus \( \tau_s \). Von Mises stress is always positive in sign, depends on the whole stress field (Cauchy tensor and the normal unit vector at the interface in the plane orthogonal to the tooth axis \( s \)) and it is evaluated for restorative materials at interfaces with post and composite-core) can be critical from a failure point of view and can exhibit a fragile failure behaviour. Accordingly, Rankine stress measures \( \sigma_{R1}, \sigma_{R2} \) (defined as maximum and minimum principal stress, respectively) are used to define the following functions of \( z \):

\[
\sigma_{R1}^*(z) = \max_{(x,y)} \sigma_{R1}(x,y,z), \quad \sigma_{R2}^*(z) = \min_{(x,y)} \sigma_{R2}(x,y,z).
\]

Functions (3) are evaluated for both residual dentin and restorative-material interfaces. In the first case they can be considered as risk indicators with respect to the root fracture, whereas at the interfaces they give a measure of the local cohesive failure-risk.

Finally, shear stress modulus \( \tau_s \) is computed at the generic point \( P \) of a given interface as: \( \tau_s = \sqrt{\begin{vmatrix} Tn \end{vmatrix}^2 - n'^Tn} \), where \( T \) and \( n \) are the stress Cauchy tensor and the normal unit vector at the interface in \( P \), respectively. Accordingly, the mean shear stress \( \tau_{s/m}^* \) (c) can be defined as the following positive function:

\[
\tau_{s/m}^*(z) = \frac{1}{A_r(z)} \int_{A_r(z)} \tau_s(x,y,z) \, dA,
\]

and it is evaluated for restorative materials at interfaces with post and dentin, where high values of the mean shear stress can lead to the post-system detachment. Therefore, function (4) gives a measure of the interfacial adhesive failure-risk.

Functions (2)–(4) are computed through an ad hoc post-processing Fortran-code, considering a discrete variation of the \( z \) coordinate and taking as input by the solver code some primary geometrical and topological data (i.e. nodal coordinates and elements which lies on the interfaces) as well as stress solutions at the integration points.

3. Results

3.1. Preliminary results: PDL modelling influence

In order to investigate the PDL modelling influence on the tooth stress distributions, preliminary numerical analyses are performed considering several constraint conditions:

- tooth perfectly fixed at any point of the PDL’s region (FX);
- tooth connected to the cortical bone (assumed rigid and fixed) through a three-dimensional continuous PDL layer (with a variable thickness along \( z \) as assumed in Fig. 4), characterized by an isotropic linearly elastic behaviour with \( E = 68.9 \) MPa, \( v = 0.45 \) (Ko et al., 1992; Pegoretti et al., 2002) and discretized through 10-nodes tetrahedral elements like the other involved volumes (IEL);
- tooth connected to the cortical bone through the proposed discrete PDL model based on the high deformation rate response (HDR);
- tooth connected to the cortical bone through the proposed discrete PDL model based on the low deformation rate response (LDR).

With reference to the healthy tooth and the pulpless tooth restored with a single carbon-fibre PCP and under the discussed loads, Figs. 5 and 6 show the Von Mises stress distributions on the tooth’s cross-section at \( y = 0 \) and the Rankine stress functions \( \sigma_{R1}^*(z), \sigma_{R2}^*(z) \) at the dentinal region, respectively.

As it clearly appears, numerical results relevant to the FX constraint condition show a deeply different behaviour for both dentin and restorative structure in comparison with the other PDL models. In detail, unrealistic stress distributions arise, characterized by very high cervical peaks and by the complete absence of a statical response in middle and apical regions. Nevertheless, even if the three tested PDL elastic models (IEL, HDR and LDR) induce comparable stress distributions inside the tooth, differences appear at the residual dentin and near the PDL’s region, especially at the apex zone. In detail, the IEL model induces a significant reduction of the apical stress peaks in comparison with those evaluated through the discrete PDL models. On the other hand, stress distributions related to HDR and LDR models are qualitatively and quantitatively similar but, in order to compare the bearing-capacity produced by different restoration techniques and the relevant fracture risk on the residual dentin, using LDR model is clearly much more conservative in an engineering sense (see Fig. 6). Therefore, all numerical simulations presented in what follows are based on the discrete PDL model with a quasi-static low deformation rate response (LDR).

3.2. Stress analysis

Von Mises stress distributions on the tooth’s cross-section at \( y = 0 \) are depicted in Fig. 7. Moreover, Fig. 8
shows the mean Von Mises stress function $\sigma_{VM}(z)$ at the residual-dentin region, whereas Fig. 9 illustrates $\sigma_{VM}$ path-plots along (see Fig. 2) the line ($y = 0, z = 12.5$).

It clearly appears that the oblique load is more critical than the vertical one, both for restoration structures and residual dentin. Moreover, the results' analysis shows a deeply different behaviour between cast gold-alloy restoration and natural tooth's. In detail, as far as residual dentin is concerned, a significant reduction of the mean stress level is obtained at the middle/cervical root zone, whereas high
peaks of the average stress are induced at the root apex. Furthermore, high stress concentrations at the post-dentin interface appear (see Fig. 9).

In the case of single-PCP restorations, dentinal mean stresses are clearly comparable with those of the natural tooth at the middle/cervical zone. Nevertheless, significant apical peaks appear both employing carbon-fibre and glass-fibre posts. Peaks are highly reduced (of about 27% for the intrusive load and 20% for the oblique one) when multi-post restorations are considered, in a way which does not depend substantially on the PCP’s material. Moreover, in these cases stress levels are lower than in the single-PCP restorations at the middle/cervical zone, especially when carbon-fibre SA-restorations are experienced (see Fig. 8). On the contrary, analysis of Figs. 7 and 9 highlights that PCP-restorations induce high values of Von Mises stress inside the posts as well as at their interfaces, mainly when carbon-fibre posts are employed, because of their high stiffness. On the other hand, since glass-fibre posts are more flexible (see Table 1), their use produces lower stress gradients between the restorative materials. Accordingly, multi-post restorations based on glass-fibre posts minimize stress gradients at post’s interfaces and therefore stress fields are more smooth and similar to the natural tooth’s. Results of numerical simulations highlight also that the above-mentioned advantages are enhanced when PCPs’ transversal dimensions and number increase.

It is worth to observe that, under oblique load, the central post in triple-post restorations (i.e. post 2 in Fig. 2) is poorly exploited from a static point of view, as it happens for traditional single-PCP restorations. This occurs because this post lies practically on the bending plane of the restored tooth, and therefore bending moment arising from the horizontal load component does not put it substantially under stress. On the other hand, the central post contributes significantly to the load transmission mechanisms when vertical loading components appear, reducing stress levels into the lateral posts (i.e. posts 1 and 3 in Fig. 2) and contributing to smooth the stress distributions.

3.3. Risk-analysis of root-fracture

Numerical results relevant to the Rankine stress functions $\sigma_{Re}(z)$ and $\sigma_{Ri}(z)$ at the dentinal region are shown in Fig. 10. It can be noted that, with respect to single-post
restoration and both for tensile and compressive stresses, multi-post solution induces a significant reduction of the tensional peaks on dentin at the apical level as well as a decrement at the cervical region. This trend appears both for vertical and oblique loads and it is much more evident in the case of SA-restorations. Accordingly, differences...
between natural and restored tooth are minimized using multi-post technique, whereas for both cast gold-alloy post and single-PCP restorations they significantly appear.

The risk of root-fracture at the apex is minimized in the case of SA-restorations with \( n_{PCP} = 3 \) and it is reduced with respect to single-PCP restorations and to cast gold-alloy post of about 42%. On the contrary, cast gold-alloy post exhibits the best performance at middle/cervical root region. Nevertheless, multi-post restorations are certainly better than single-PCP ones: for instance, SA-restorations with \( n_{PCP} = 2 \) reduce the root-fracture risk at cervical region of about 25%.

3.4. Risk-analysis of interface-failure

As far as PCP-interfaces are concerned, bounding both filling cement and composite-core, Fig. 11 depicts Rankine stress functions \( \sigma_{Rc}(z) \) and \( \sigma_{Rt}(z) \), whereas Fig. 12 shows the results relevant to the mean shear stress \( \tau(z) \), introduced in (4). Moreover, their graphs relevant to the dentinal interface are depicted in Fig. 13.

Rankine and mean shear stress functions at PCPs’ interfaces are strongly influenced, for both loadings, by material, dimensions and position of the posts. When vertical load is considered, multi-post treatments induce a reduction of the mean shear stresses (i.e. of the adhesive interfacial failure-risk) with respect to single-PCP restorations, especially at filling-cement interface and for OA-cases, whereas the Rankine interfacial stresses (related to the cohesive failure-risk) do not change substantially.

On the contrary, as far as oblique loads are concerned, absolute values of functions (3) and (4) in multi-post solutions can be higher than for single-PCP treatments. This is experienced for the posts more distant from the tooth axis, i.e. far from the bending plane. However, Figs. 11 and 12 confirm that when glass-fibre posts are employed the interfacial stress peaks exhibit a strong reduction (ranging from 30% to 45%) with respect to multi-post carbon-based restorations, minimizing the adhesive/cohesive interfacial failure-risk.

Finally, cast gold-alloy post induces high stress concentrations also at the dentinal root-cavity interface, whereas PCP-systems produce significantly lower shear and normal stresses, especially when single-PCP solution is employed. Multi-post carbon-based restorations experience mean shear stresses comparable to those of the cast gold-alloy post at the apical region. Nevertheless, Fig. 13 highlights that no significant differences appear between single- and multiple-PCP treatments when glass-fibre posts are employed. Therefore, multi-post restorations based on glass-fibre PCPs minimize also detachment risks at the root-cavity interface.

4. Discussion and conclusions

In this paper the mechanical response to parafunctional loads of endodontic restorations based on multiple prefabricated composite posts (PCP) is investigated through three-dimensional elastic finite-element analyses. The influence of number, material and dimensions of the
Fig. 11. Rankine stress functions $\sigma_{Rt}(z)$ and $\sigma_{Re}(z)$ at post interfaces. Vertical (above) and oblique (below) loading conditions.

Fig. 12. Mean shear stress function $\tau_n(z)$ at post interfaces. Vertical (above) and oblique (below) loads. The symbols are the same of Fig. 11.
posts is analysed and the periodontal ligament (PDL) effect is taken into account. In detail, an elastic anisotropic non-linear discrete model, based on a quasi-static experimental PDL response, is employed. This approach produces realistic stresses on the tooth and is conservative in the sense of the bearing capacity evaluation for the restored structure, in comparison with other modelling methodologies.

In addition to the shrinkage effects’ minimization due to the high reduction of the polymerization volumes undergoing contraction phenomena, the multi-post technique exhibits many other inherent advantages, demonstrated by numerical simulations. Firstly, multiple PCPs fill large and irregular root cavities more efficiently than a single central post. Moreover, unlike traditional cast gold-alloy posts that produce high stress gradients at the root-cavity interface, rational disposition of fibre-reinforcements far from the tooth axis induces into the restored tooth a stress state uniform and homogeneous, very similar to the natural tooth’s. Accordingly, multi-post restorations lead to a better reproduction of the natural load transmission mechanisms.

Moreover, comparisons with single-post and cast gold-alloy restorations show as multi-post technique produces a significant reduction of the stress levels into the healthy tissues, especially at the apical region, reducing the risk of irreversible root fractures. This positive aspect seems to increase when the cross-section area of the posts increases.

Finally, the choice of the posts’ material appears very important when the failure-risk at post- and dentin-interfaces is considered. Interfacial stresses occurring in multi-post restorations equipped with carbon-fibre PCPs can be higher than those in single-PCP cases, while the experienced stresses remain certainly acceptable if glass-fibre PCPs are employed. Adhesive and cohesive interfacial failure-risk is therefore strongly reduced in the last case and a longer restoration durability to fatigue-cyclic loadings can be stated with respect to both cast gold-alloy post and traditional single-PCP restorations.

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