Coupling image processing and stress analysis for damage identification in a human premolar tooth

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\textbf{Abstract}

Non-curious cervical lesions are characterized by the loss of dental hard tissue at the cement-enamel junction (CEJ). Exceeding stresses are therefore generated in the cervical region of the tooth that cause disruption of the bonds between the hydroxyapatite crystals, leading to crack formation and eventual loss of enamel and the underlying dentine.

Damage identification was performed by image analysis techniques and allowed to quantitatively assess changes in teeth. A computerized two-step procedure was generated and applied to the first left maxillary human premolar. In the first step, dental images were digitally processed by a segmentation method in order to identify the damage. The considered morphological properties were the enamel thickness and total area, the number of fragments in which the enamel is chipped. The information retrieved by the data processing of the section images allowed to orient the stress investigation toward selected portions of the tooth. In the second step, a three-dimensional finite element model based on CT images of both the tooth and the periodontal ligament was employed to compare the changes occurring in the stress distributions in normal occlusion and malocclusion. The stress states were analyzed exclusively in the critical zones designated in the first step.

The risk of failure at the CEJ and of crack initiation at the dentin–enamel junction through the quantification of first and third principal stresses, von Mises stress, and normal and tangential stresses, were also estimated.

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1. Introduction

Non-curious cervical lesions (NCCL) are characterized by the loss of dental hard tissue at the cement-enamel junction (CEJ) \cite{1,2}. Traditionally this has been assumed to be due to the effects of abrasion and/or erosion. More recently cervical tooth loss has been linked with cuspal flexure. It has been suggested that occlusal loads cause the teeth to flex, particularly during lateral excursion. As the tooth flexes, tensile and shear stresses are generated in the cervical region of the tooth that cause disruption of the bonds between the hydroxyapatite crystals, leading to crack formation and eventual loss of enamel and the underlying dentine \cite{3,4}. Grippo \cite{5} coined the term “abfraction” to distinguish this type of cervical tooth loss associated with cuspal flexure. During clenching, occlusal forces are applied along the long axis of the tooth. In this case, forces dissipate, and thus the distortion of enamel and the dentinal crystal is minimal. However, during mastication, lateral forces appear, which cause the tooth to bend. This pro-
roduces larger tensile stresses acting on the CEJ, which brings about the disruption of chemical bonds in the enamel and the dentine crystalline structures, leading to separation of enamel from the dentine [6]. Burke et al. [7] have cited the following factors in support of a cuspal flexure theory of cervical tooth loss:

- these lesions occur in teeth subjected to lateral load, but adjacent teeth not subjected to these forces remain unaffected;
- these lesions are rarely seen on the lingual aspects of teeth;
- the lesions may occur sub-gingivally. This would not be the case for erosion or abrasion lesions.

Although many investigators [8–10] have supported this theory, only a few biomechanical studies have demonstrated the role of tooth flexure in the development of abfraction lesions [11–14]. Previous finite element [9] and strain-gauge studies [10] have demonstrated high stress concentrations in the thin cervical enamel area, and the magnitude of these stresses exceeded the known failure stresses for enamel. A number of studies [2,5,15,16] have suggested that there may be a variation in the prevalence of cervical lesions, affecting different tooth types. The results of these studies indicate that the most affected teeth are premolars [15].

The cervical area has a weak mechanical bond between enamel and dentine because of the lack of a scalloping pattern of CEJ. In fact, this is a toughening mechanism which improves the fracture-resistant properties of the junction: prisms interlock with each other forming wavy junctions which inhibit crack propagation. In theory, any occlusal contact that can generate tensile stress at the cervical area has a possibility to create a cervical lesion. In a FE study, Lee et al. [11] found that when lateral loads were applied, tensile stresses generated on the cervical areas were higher than when vertical loads were applied at the same areas. Borcic et al. [17] showed that the malocclusion with heavy lateral occlusal force generated much higher tensile stress on the tooth, which may have caused a higher prevalence of cervical lesions. The increase in the load did not cause a change in the overall stress pattern but increased the values. The loading to which the tooth was subjected may have caused cracks in the tooth, but not necessarily its immediate failure. It is notable that the large tensile stress was concentrated at the cervical region on the buccal side in the model where occlusion was not ideal. The oblique force loaded on the palatal cusps produced distortion of the tooth and caused enamel at the cervical region to stretch. Various studies [4,6,11,18] have shown that a lateral force causes bending of the tooth and that stress acting on the tooth brings out the disruption of chemical bonds between the enamel crystals. Enamel is far more brittle (and has higher modulus of elasticity) than dentine. In brittle materials, compression has far lower effect than an equal amount of tension. Shear stress is in fact more detrimental than tensile stress. This chipped enamel can accelerate the development of caries when dentine is exposed to the oral cavity environment. Koran and Craig [19] confirmed by the photoelastic method that an oblique force loaded on the tooth causes stress concentration at the cervical line. Darendellier et al. [20] showed that the shear stresses both of which were smaller than the maximum compressive-yield stresses, generated fracture of the tooth. Lee et al. [11] and Lee and Eakle [4] argued that a lateral occlusal force produced compressive stress on the side toward which the tooth bent, and tensile stress on the opposite side. Spears et al. [21] showed that a vertical force loaded at one tip of the lingual cusp of the mandibular second premolar produces tensile stress at the lingual enamel on the cervical region. Tanaka et al. [6] demonstrated that an occlusal force loaded on the lingual tip of the premolar produces the tensile strain at the cervical region on the buccal side.

Changes in teeth due to NCCLs can be quantitatively assessed by image analysis techniques. In fact, the improvement in digital image acquisition devices has allowed some attempts for this purpose. In a study by Kaczmarek et al. [22] the boundary between the enamel and the dentin was detected and quantitative measurements were performed. The obtained results allowed to show the range of carious lesions in fissure sealant and unprotected human premolars. The aim was to quantitatively assess caries changes of teeth by digital image analysis, that was performed manually.

In a study by Imbeni et al. [23] the propagation of cracks initiated in the enamel was studied and the results were confirmed by visual inspection considering images taken by the scanning electron microscope (SEM). In the work of Kruzic et al. [24] the effect of hydration over crack blunting and on the fracture mechanics are studied. Microscopy and X-ray tomography were considered. Also in this case the images were considered to confirm the experimental results and no image analysis was performed. In Kantapanit et al. [25], dental caries lesions were detected using deformable polygonal templates and edge information of teeth were found by Canny edge detector.

The aim of this paper is to propose a computerized two-step procedure for detection of damage due to NCCL in human premolars. In the first step, dental images in the surroundings of the CEJ are digitally processed by the segmentation method in order to identify the damage. In other words, the deteriorated portions of the enamel layer were marked out, and the damage extent was estimated by evaluating damage parameters such as enamel thickness, total area and Euler number used for counting the number of fragments of enamel tissue. In the second step, the stress distributions are analyzed in the critical zones by the finite element method to numerically evaluate the risk of failure. In particular, a three-dimensional model of the first maxillary premolar was used to compare the stress profiles between the two loading conditions of normal occlusion (NO) and malocclusion (MO). Moreover, the adhesion and cohesion conditions at the enamel–dentine interface were studied. The premolar was chosen because a previous study [15] confirmed that every third premolar was affected by some form of NCCL, and a two-rooted tooth was used as model for studying an NCCL [17].

2. Materials and methods

The mechanical properties of the enamel, dentine, pulp and periodontal ligament are given in Rees et al. [16], Eskitascioglu et al. [26], Lin et al. [27], Zhou and Zheng [28] and are shown in Table 1. The materials of the various tooth structures were
assumed to be isotropic, homogeneous and linearly elastic. They remained constant under the monotonically statically applied loads.

2.1. Generalities

In the following subsections a computerized two-step procedure is outlined for detection damage due to NCCL in human premolars. In the first step (Section 2.2) dental images (Fig. 1a) in the surroundings of the CEJ are digitally processed by a segmentation method, in order to identify damage. In the second step (Section 2.3) a geometric model (Fig. 1b) based on micro-CT images of both tooth and periodontal ligament has been constructed; the micro-CT images were acquired with a medical CT scanner. The height of the tooth was 23.74 mm. The stress states both in normal occlusion and malocclusion were investigated in the critical zones by the FE method in order to numerical evaluate the risk of failure.

2.2. Image processing

Digital image analysis of the complete set of the horizontal sections of the upper left first premolar was performed to check if a fracture was present and where it was located. Though the images appeared of good quality, a preprocessing was advisable. A $\gamma$-correction was considered to enhance the enamel; given the gray level $r$, the $\gamma$-correction is the non-linear operation: $r' = r^\gamma$. Fig. 2 represents the effect of the $\gamma$-correction for increasing value of $\gamma$: 0.3, 0.7, 1 (original data), 1.2, 1.7 on the cross-section at $z = 8.381$ mm. Note that for $\gamma > 1$ an image darker than the input one is obtained. Opposite effects are generated with $\gamma < 1$. Since the enamel is the region of the image with the higher gray level, for the considered sequence a $\gamma$-correction with $\gamma = 1.5$ was chosen and with this correction the background (the dentin and the pulp) is darkened and therefore the enamel has been enhanced. A greater value of $\gamma$ would have enhanced also the noise.

To clearly identify the enamel and distinguish the latter from the dentine, a segmentation is needed. Image segmentation is a partition of the image into regions homogeneous with respect to some properties, e.g. the gray level, the texture, the color, the shape, and so on, with no loss of the information of interest. In this case, as already noted, what characterized the enamel was its gray level that was the highest in the images (Fig. 1a). Therefore, to identify the enamel, a segmentation with respect to gray level was considered [29]. A $n$-level segmentation produces a cartoon-like image; in particular a two-levels segmentation, that is a binarization, is a white and black image. A simple method to binarize an image is to choose a threshold and assign value one to all the pixels with gray

<table>
<thead>
<tr>
<th>Table 1 – Mechanical properties of materials.</th>
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<td>Properties</td>
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<td>------------</td>
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<tr>
<td>Pulp</td>
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<td>Periodontal ligament</td>
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Fig. 1 – Tooth model: (a) stacked CT images and (b) geometry and section levels.
level greater than the threshold and zero to the others. The result obviously strongly depends on the chosen threshold. The Otsu method [30] allows to find the optimal threshold to binarize the image; it can be used also for n-levels segmentation. For the considered images a four levels segmentation was advisable. The Otsu method was applied hierarchically: first a binarization, obtaining a black and white image, and then each region (the white region and the black one) is further binarized, obtaining the four level segmentation. The obtained segmented image is a simpler representation of the original data. The enamel is the object with the highest gray level (represented in white color) and by simple logical operation it can be easily identified. On this image useful information may be retrieved, like morphological properties of the objects present in the scene, e.g. the geometrical characteristics like the area, the thickness and the Euler number of the enamel layer. The Euler number is the difference between the number of objects and the holes present in the image. For example, when the enamel constitutes a unique non-fragmented object (similar to an elliptic ring) the Euler number is equal to zero (one object, the enamel, minus one hole, that is the space inside the enamel). This information helps in determining whether the enamel exhibits one or more lesions. More precisely, analyzing a sequence of cross-sections, a sudden change in one of the above mentioned geometrical properties may indicate the presence of a lesion. If one observes that in some cross-

![Fig. 2 - Effect of the γ-correction for increasing value of γ: 0.3, 0.7, 1, 1.2, 1.7 from left to right on the cross-section at z = 8.381 mm.](image)

![Fig. 3 - Loading conditions: (a) normal occlusion and (b) malocclusion.](image)
sections the enamel is fragmented, it can be useful to count the number of pieces in which the enamel is divided, the Euler number and the site where the fracture is localized. All these data can be collected for each cross-section of the available sequence.

2.3. Finite element method

Improved computer and modelling techniques render the finite element method (FEM) a very reliable and accurate approach in biomechanical applications. In this paper, three-dimensional finite element analyses were performed on a human intact maxillary first premolar in order to address the problems mentioned in the Introduction. An accurate finite element model based on CT images of both the tooth and periodontal ligament has been employed. Tetrahedral elements have been used to construct the model and the contact options of full bond between periodontal ligament and maxillary bone have also been used.

The finite element model was constructed from the contours of each morphological entity (dentine, enamel, periodontal ligament and pulp) obtained from successive 541 CT images (Fig. 1a). The CT images were available at a spacing of 43.882 μm, thus allowing an accurate description of tooth anatomy to be obtained, Fig. 1b.

The outline of the periodontal ligament 0.3 mm wide was generated using the outline of the tooth as a guide. The dimensions of the periodontal ligament were derived from the literature [31,32]. The solid model was transferred into the FEM program Comsol 3.4. A three-dimensional mesh was created, and the stress distribution analysis was performed. Boundary conditions have been established on the outer surface of the surrounding ligament. By invoking the Boussinesq’s local perturbation principle, it has been estimated that the boundary conditions were applied far enough from force application point to not significantly influence the stress distribution in different parts of the tooth. Therefore, the ligament was clamped (all displacements fixed), thus preventing rigid body displacements in directions of all three coordinate axes. In these analyses, the contact with neighbouring teeth was not modelled by applying specialized contact elements. In fact, contact modelling would unnecessarily increase the complexity of the model without significantly influencing the final results.

Nine-nodded tetrahedral elements were applied in the discretization of the tooth morphology, resulting in 152,052 elements and 29,487 nodes with 657,543 degrees of freedom. In the case of normal occlusion, three forces were applied to the occlusal surface. The forces were applied at the palatal incline of the buccal cusp, at the buccal incline of the palatal

<table>
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<th>Table 2 – Loading conditions.</th>
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<tr>
<td>Components</td>
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<tr>
<td>Normal occlusion</td>
</tr>
<tr>
<td>$N_1$</td>
</tr>
<tr>
<td>$N_2$</td>
</tr>
<tr>
<td>$N_3$</td>
</tr>
<tr>
<td>Malocclusion</td>
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Fig. 4 – Identification of the enamel from cross-section $z = 8.38$ mm: (a) original image, (b) gamma correction, (c) binarization, (d) four levels segmentation and (e) enamel identification.

Fig. 5 – Thickness values along the distal (D), mesial (M), buccal (B) and palatal (P) directions.
Fig. 6 – Analysis of the sequence of cross-sections corresponding to $z = 6.83 - 9.03$: (a–d) thickness in the P, B, D, and M sides respectively; (e) number of enamel fragments with Euler number for each cross-section; (f) the total area of the enamel.

cusp, and at the palatal incline of the palatal cusp (Fig. 3a). In the case of malocclusion, the force was applied to the buccal incline of the palatal cusp (Fig. 3b). During the analysis, the models of the tooth were loaded with forces (Fig. 3 and Table 2) $N_1 = 70$ N, $N_2 = 70$ N, and $N_3 = 70$ N in the case of normal occlusion and $M = 200$ N in the case of malocclusion, which are assumed to be a normal chewing load. The chewing forces produced by mastication are reported to range from approx-
imately 37–40% of the maximum bite force [17,33]. The load vectors were applied to the surface in the direction normal in order to simulate the contact with antagonistic teeth. In more detail, the force components in the coordinate system of Fig. 3 are reported in Table 2.

### 3. Numerical results

#### 3.1. Data processing

A sequence of 50 images was considered. Each image is a matrix of dimension \( n \times m \) pixels, with \( n = 233 \), number of rows, \( m = 179 \), number of columns. The pixel length is equal to 0.0439 mm. For each cross-section of the considered sequence of tooth images the \( \gamma \)-correction and the four levels segmentation were performed. In Fig. 4 the cross-section at level \( z = 8.38 \) mm is analyzed: in Fig. 4a and b the original picture and its \( \gamma \)-correction (with \( \gamma = 1.5 \)) are displayed respectively; in Fig. 4c and d the binarization and the four level segmentation of Fig. 4b obtained by the adopted Otsu method are shown. Once the image has been segmented, the enamel is univocally identified by simple logic operation as the region with higher gray level, Fig. 4e. For each available tooth cross-section, the enamel may be characterized by its area, thickness in distal (D), mesial (M), buccal (B) and palatal (P) zones, the number of regions that constitute the enamel itself and the already discussed Euler number of the enamel. The area is the number of pixels constituting the enamel layer. The thickness is evaluated along the above mentioned zones over a grid superimposed to the image cross-section. A grid spacing equal to \( n/4 \) along the buccal–palatal (B–P) direction and equal to \( m/4 \) along the mesial–distal (M–D) direction was considered. The chosen grid intersects the identified enamel in twelve segments (three for each side) whose lengths, representing the thickness of the enamel in these sections, have been automatically evaluated, Fig. 5. For a better understanding, the colors of enamel and background were reversed with respect to Fig. 4e. For example, for the image of Fig. 4e the larger fragment has area equal to 1614 pixels, whereas the others have area equal to 79, 85 and 47 pixels. The number of regions, equal to four, that compose the enamel has been automatically evaluated along with the Euler number, also equal to four.

Fig. 6 shows the variation of different thicknesses in the sequence of cross-sections corresponding to \( z = 6.83–9.03 \), according to the positions indicated in Fig. 5. In Fig. 6a and Fig. 6b the thicknesses (\( P_1, P_2, P_3 \)) and (\( B_1, B_2, B_3 \)) relative to the buccal–palatal direction, palatal side (B–P/P) and relative to the buccal–palatal direction, buccal side (B–P/B), evaluated in the segments intersected by the chosen grid on the enamel are represented respectively.

Respectively, in Fig. 6c and d the thicknesses (\( D_1, D_2, D_3 \)) and (\( M_1, M_2, M_3 \)) relative to the distal–mesial direction, distal side (D–M/D) and relative to the distal–mesial direction, mesial side (D–M/M), evaluated in the segments intersected...
by the chosen grid on the enamel are represented. In Fig. 6e the number of enamel fragments and the Euler number for each cross-section are shown, whereas in Fig. 6f the total area of the enamel for each analyzed image is illustrated.

The thickness in the P side decreases showing no irregular behavior and no fracture is present. From level $z=7.76$ mm it can be noted that the thickness in the M and B sides is less than 6 pixels (corresponding to 0.2634 mm), as shown in Fig. 6b (where $B_1$ thickness is equal to zero) and Fig. 6d. The enamel is constituted of one fragment and the number of Euler is equal to one: these two characteristics mean that a fracture is present. In Fig. 7a the segmentation of the image at level $z=7.76$ mm is shown.

From level $z=8.50$ mm in the B side the thickness becomes lower, also in the M side the thickness becomes less than 5 pixels (corresponding to 0.2195 mm). Moreover the $D_3$ value is equal to zero. The thickness in the P side becomes less than ten pixels (corresponding to 0.439 mm). There are five fragments with Euler number equal to zero. In Fig. 7b the segmentation of the image at level $z=8.50$ mm is presented.

From level $z=8.59$ mm the thickness becomes definitively less than five pixel in the B, D and M sides, whereas the number of enamel fragments and the Euler number are both equal to five. In Fig. 7c the segmented image at level $z=8.59$ mm is shown.

From level $z=8.63$ mm the damaged zone begins and in the D and M sides the thickness becomes less than four pixels (corresponding to 0.175 mm), see Fig. 7f for the segmented image at level $z=8.63$ mm.

From level $z=8.85$ mm only in the P side the thickness is more than five pixels (corresponding to 0.219 mm) and twelve enamel fragments are present. No holes are present therefore the Euler number is equal to twelve too. The segmentation of section at level $z=8.85$ mm is shown in Fig. 7e.

In the section at level $z=8.94$ mm (see Fig. 7f) there are ten fragments and the thickness of the enamel is less than five pixels except in $P_1$ and in $P_3$ thicknesses.

### 3.2. Stress analyses

A detailed description of the stress distribution was based on 30 horizontal sections at the CEJ (Fig. 1b) and on the enamel/dentin junction. Fig. 1b reports the levels $z_1=7.450$ mm and $z_2=9.030$ mm of the extremal cross-sections measured with respect to the buccal cusp. Figs. 8–11 show differences in the stress distribution between the two models under different loading conditions. Two typical cases have been considered: the tooth under normal occlusion (Fig. 3a) and the tooth under malocclusion (Fig. 3b).
Fig. 10 – Histogram of the Mises stress $\sigma_M$ (MPa): (a) normal occlusion and (b) malocclusion.

Fig. 11 – Histogram of the maximum shear stress $\tau_{\text{max}}$ (MPa): (a) normal occlusion and (b) malocclusion.

The results are presented as maximum and minimum principal stresses ($\sigma_1$ and $\sigma_2$), Figs. 8 and 9. Positive and negative values indicate that the corresponding regions are subjected to tensile or compressive stresses, respectively. Furthermore, the fields of Mises stress ($\sigma_M$, Fig. 10) and maximum shear stress ($\tau_{\text{max}}$, Fig. 11) were analysed to estimate the risk of failure in the models. In more detail, each row of the histograms in Figs. 8–11 refers to a single cross-section and indicates the sector where the maximum/minimum value is attained by the stresses $\sigma_1$, $\sigma_3$, $\sigma_M$, and $\tau_{\text{max}}$ at the relevant section. Each cross-section is identified by its height $z = z_1 - z_2$ (Fig. 1b), on the ordinate axis.

Moreover, the components $t_x$, $t_y$, $t_z$, of the surface traction $t$ on the enamel–dentin junction (EDJ) were calculated and represented in the global $x$, $y$, and $z$-direction (Fig. 12), in order to evaluate the largest tensile and shear stresses causing possible detachment and/or slippage in normal and tangential directions with respect to the EDJ. In particular, the zones 1 and 2 in Fig. 12 indicate the points where the tensile and shear stresses attained their maximum values. The tensile stress $\sigma_0$ acts in direction normal to the surface of the EDJ, whereas the shear stress $\tau$ represents the effort exerted in the plane tangent to the above mentioned interface EDJ.

This study is devoted to predict the variations in the values of first and third principal stresses, Mises stresses, and surface traction components in the two different loading conditions, namely normal occlusion (Figs. 8a–11a) and malocclusion (Figs. 8b–11b).

With reference to Fig. 8a ($\sigma_1$, NO, $z = 7.670$–$8.942$ mm), it can be observed that in the range from $z = 7.670$ mm to zone 1

zone 2

Fig. 12 – Interface between enamel and dentin.
Fig. 13 – Distribution of the Mises stress $\sigma_M$ (MPa): (a) normal occlusion ($z = 8.328$ mm) and (b) malocclusion ($z = 8.854$ mm).

$z = 8.328$ mm the first principal stress in normal occlusion attains its larger values in the PM sector in the enamel on its outer surface; from $z = 7.802$ mm to $z = 8.284$ mm the highly stressed zones spread over the thickness of the enamel in the same sector more uniformly than in the lower band. In the upper part from $z = 8.328$ mm to $z = 8.942$ mm, the largest values migrate toward the M sector and concentrate where the enamel gets thinner and vanishes leaving place to the dentin; the absolute maximum is reached in the M sector at $z = 8.767$ mm and is 9.7 MPa.

Fig. 9a ($\sigma_3$, NO, $z = 7.670$–8.942 mm) shows that in the range $z = 7.670$–7.845 mm the maximum absolute value ($z = 7.758$ mm, $\sigma_3 = -81.8$ MPa) of the third principal stress in normal occlusion is located in the MB sector on the outer surface of the enamel; from $z = 8.416$ mm to $z = 8.942$ mm the highly stressed zones migrate toward the PM sector, passing through the M–PM sector ($z = 8.371$ mm) and the M sector from $z = 7.88$–8.328 mm. They concentrate where the enamel gets thinner and vanishes leaving place to the dentin; the absolute maximum is reached in the M sector at $z = 8.284$ mm and is $-88.0$ MPa.

Fig. 10a shows that in the range $z = 7.670$–7.845 mm the local maximum value ($z = 7.758$ mm, $\sigma_M = 75.0$ MPa) of the Mises stress in normal occlusion is located in the MB sector on the outer surface of the enamel. From $z = 8.196$ mm to $z = 8.942$ mm the highly stressed zones migrate toward the PM sector, passing through the M–PM sector ($z = 8.371$ mm) and the M sector (from $z = 7.88$ mm to $z = 8.328$ mm). They concentrate where the enamel gets thinner and vanishes leaving place to the dentin. The absolute maximum is reached in the M sector at $z = 8.328$ mm and is 82.3 MPa.

Fig. 11a shows that in the range $z = 7.670$–7.845 mm the local maximum value ($z = 7.758$ mm, $r_{\text{max}} = 40.6$ MPa) of the maximum shear stress in normal occlusion is located in the MB sector on the outer surface of the enamel. From $z = 8.196$ mm to $z = 8.942$ mm the highly stressed zones migrate toward the PM sector, passing through the M–PM sector ($z = 8.371$ mm) and the M sector (from $z = 7.88$ mm to $z = 8.328$ mm). They concentrate where the enamel gets thinner and vanishes leaving place to the dentin. The absolute maximum is reached in the M sector at $z = 8.328$ mm and is 43.65 MPa. A second local maximum is found in the PM sector at $z = 8.635$ mm and its value is 38.25 MPa.

The Mises stress distribution exhibits the same pattern as the third principal stress in the range $z = 7.670$–8.942 mm. Fig. 13 shows the distribution of the Mises stress at the level $z = 8.328$ mm, where the absolute maximum value is attained.

With reference to Fig. 8b ($\sigma_1$, MO, $z = 7.450$–8.723 mm), it can be observed that the first principal stress exhibits its maximum value 107 MPa at $z = 7.889$ mm on the MB side in the enamel; then, the largest values of $\sigma_1$ decrease by passing from B ($z = 7.450$–7.582 mm) and MB sectors ($z = 7.626$–7.889 mm) to D sector ($z = 8.591$–8.723 mm) through the M ($z = 7.933$–8.328 mm) and BD ($z = 8.372 – 8.548$ mm) sectors, still in the enamel.

With reference to Fig. 9b ($\sigma_3$, MO, $z = 7.760$–9.030 mm), the largest values of the third principal stress are uni-
Table 3 - Maximum and minimum principal stresses, Mises stress, and maximum shear stress in the cervical region.

<table>
<thead>
<tr>
<th>Sector</th>
<th>σ1 (MPa)</th>
<th>σ3 (MPa)</th>
<th>σM (MPa)</th>
<th>r_max (MPa)</th>
</tr>
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<tr>
<td>NO</td>
<td>9.7</td>
<td>−88.1</td>
<td>82.3</td>
<td>43.65</td>
</tr>
<tr>
<td>MO</td>
<td>107.0</td>
<td>−159.2</td>
<td>181.0</td>
<td>82.65</td>
</tr>
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formally distributed in the P (z = 7.760–7.977 mm) and PM (z = 8.021–8.416 mm) sectors of the enamel near the interface with the dentin; then, they tend to concentrate in the P sector (z = 8.899–9.030 mm) on the outer surface of the enamel, where they reach the maximum value −159.2 MPa at z = 8.942 mm. The passage through the M (z = 8.460–8.679 mm) and PM (z = 8.723–8.854 mm) sectors encounter two local maxima −135.1 MPa at z = 8.591 mm in the M sector and −136.1 MPa at z = 8.854 mm in the PM sector.

With reference to Fig. 10b (σM, NO, z = 7.760–9.030 mm), the Mises stress gets even larger (181.0 MPa) in the PM sector (z = 8.635–9.030 mm) at z = 8.854 mm; the peak values are always confined at the tip of the enamel layer of vanishing thickness; for completeness’s sake, the other two local maxima 110.5 MPa at z = 7.760 mm and 137.3 MPa at z = 8.591 mm are attained respectively in the MB sector (z = 7.760–7.845 mm), and in the M sector (z = 7.889–8.591 mm).

With reference to Fig. 11b (r_max, MO, z = 7.760–9.030 mm), the maximum shear stress gets even larger (82.65 MPa) in the PM sector (z = 8.635–9.030 mm) at z = 8.942 mm; the peak values are always confined at the tip of the enamel layer of vanishing thickness; for completeness’s sake, the other two local maxima 60.0 MPa at z = 7.848 mm, 58.25 MPa at z = 8.372 mm, and 73.95 MPa are attained respectively in the MB sector (z = 7.760–7.845 mm), in the M sector (z = 7.889–8.591 mm), and in the PM sector (z = 8.635–9.030 mm).

Fig. 13b shows the distribution of the Mises stress at the level z = 8.854 mm, where the absolute maximum value is obtained.

It should be remarked that both absolute and local maxima of the Mises stress were attained exactly at the sections where the data processing performed in Sections 2.2 and 3.1 found out minimal thicknesses of the enamel layer; the same observation does hold with very good approximation also for the maximum shear stress.

In the case of normal occlusion, larger compressive stresses and tensile stresses, and maximum shear stresses were found inside the enamel at the mesial side. In the case of malocclusion, larger compressive stresses were found at the palatal side, whereas larger tensile stresses were found at the mesial–buccal sector, still inside the enamel; the largest maximum shear stress was localized at the palatal–mesial sector inside the enamel at the CEJ. Table 3 shows the values of the maximum and minimum principal stresses, of the Mises stress and of the maximum shear stress in the cervical regions for the case of NO and MO. In case NO, the peak values for the principal stress values ranged from −88.0 MPa to +9.7 MPa in the cervical areas; the maximum shear stress attained the extremal values of 15.35 MPa and 43.65 MPa in the same zone. Case MO shows significant variation in stress values. In this case, results show increase in stress values to be reaching and tensile stress of 107.0 MPa in mesial–buccal region and compressive stress of −159.2 MPa in the palatal region; the smallest and largest values of the maximum shear stress were 35.5 MPa and 82.65 MPa in the mesial and palatal–mesial sectors respectively.

As far as the interface between enamel and dentin is concerned, the vector of the surface traction t may be a suitable measure of the stress state which could possibly initiate debonding and slippage between the two tissues. Normal stress σn is obtained projecting the surface traction t in direction n of the outward normal to the surface:

\[ σ_n = t \cdot n \]  

(1)

whereas shear stress τ is derived subtracting the normal stress vector σn to the surface vector t and evaluating the intensity of the resultant vector:

\[ τ = |t - σ_n n| \]  

(2)

If the axial stress σn normal to the surface and the shear stress τ tangent to the enamel–dentine junction should exceed the limits of the adhesion and cohesion strengths, σa, σc, relative motion could onset between the two tissues.

In the case of normal occlusion (Table 4), two sites seemed to be candidate as the critical ones: the first is the zone 1 shown in Fig. 12, where the components of the surface traction vector t in the coordinate system of Fig. 3 are t_x, t_y, t_z, and the unit vector n of external normal has components n_x, n_y, n_z. Therefore, Eq. (1) and Eq. (2) give: σ_n = −12 MPa and τ = 12 MPa respectively. The second side is placed at the zone 2 indicated in Fig. 12, where Eq. (1) yields σ_n = 16 MPa, and Eq. (2) yields τ = 19 MPa. In the case of malocclusion, the zone 1 appears to be the most stressed portion of the interface: σ_n = −36 MPa, τ = 31.5 MPa (Table 5).

4. Discussion

The analyses of CT image sequence provided information about variations of morphological characteristics of the
enamel in a premolar tooth by a segmentation procedure. This investigation succeeded not only to confirm experimental results or to verify a posteriori lesions on the tooth, as is currently done in literature, but to a priori localize damage via automatic processing.

The analysis of specific properties, namely enamel thickness in different points and number of fragments in which the enamel was divided, along with the Euler number, allowed the identification of the zones of the enamel in which a weakness was present.

The information given by the above-described data processing led to the successive FEM analysis of the constructed model of the premolar geometry, in order to limit the mechanical characterization exclusively to the critical zones. In fact, significant variations were confirmed in the compressive and tensile stress values in the enamel and dentine at the cervical area in two different loading conditions (normal and malocclusion). Understanding of the cervical lesions is important for the clinical treatment and restoration of damage. This study implied the assumption that occlusal forces played a role in noncarious lesions. In the case of malocclusion, the occlusal force caused the tooth to bend by pushing against the tooth axis, and higher tensile stresses were produced on the cervical region. Enamel and dentin were modelled as isotropic and the FEM model represented a static situation. Enamel structure varies in different directions, and thus possesses structural anisotropy; however, in the relevant literature it is known to be only moderately anisotropic with a ratio of 0.8 for modulus and 1.4 for toughness across the rods as compared to the orthogonal direction. The mechanical anisotropy as well as the measured gradients in hardness, all point to the fact that there is no single “correct” value for any mechanical property of enamel. In fact the enamel cap appears to be asymmetrically structurally fine-tuned, with stiffness varying from area to area. A structural asymmetry exists between the palatal and buccal sides of upper molars, and the enamel is found to be stiffer on the palatal surfaces of the enamel cap. Furthermore, both elastic and fracture properties of dentin differ by about 10% when observed along the direction of the tubules as compared with the orthogonal orientation. In computer simulations of whole-tooth deformation, the use of single values of elastic properties (moduli and Poisson’s ratios) enables simple models to be constructed, and these have provided some important insights into enamel cap function. The results obtained by simulations are clearly affected by the level of microstructure detail that is incorporated into the models. Moreover, an increased compressibility of teeth occurs at low loads. To date, none of the simulations has fully reproduced the complex structure of the enamel cap, although an increased level of detail is being achieved.

The Otsu segmentation method enjoys good performance with numerical efficiency. This is the reason for which it has been preferred with respect to other segmentation methods. The abrupt changes of geometrical parameters are significant in denouncing the possible presence of a fracture.

In the example under examination, it can be noted that the area of the enamel in the considered sequence of cross-sections did not exhibit any sharp variation, Fig. 6f. For this reason, the analysis will be devoted to alternative geometrical parameters, namely the thickness in different points, the number of regions constituting the enamel, the Euler number. A global overview of all the collected information allows to assert that in the lower part of the M side and in the B side, a weakness in the enamel is present. From a quantitative point of view, it is remarkable that the thickness at level $z = 8.328$ mm was less than 0.0878 mm in the B side and less than 0.1756 mm in the M side. At the level $z = 8.854$, the thickness was less than 0.0439 mm in the B side and less than 0.1756 mm in the M side. This observation was confirmed by the largest values attained by the Mises stress: $\sigma_M = 82.3$ MPa in normal occlusion at level $z = 8.328$ mm and $\sigma_M = 181$ MPa in malocclusion at the level $z = 8.854$.

The detailed screening carried out on the section images of the tooth at various levels allowed to select the most critical zones and hence to conduct specific analyses of the stress states thereby. In particular, the attention was devoted to the buccal, mesial and palatal–mesial sectors, where the thickness of the enamel layer underwent a dramatic drop. The stress analyses were performed within the level range $z = 7.670–9.030$ mm and were extended to loading conditions of both normal occlusion and malocclusion.

The fields of Mises stress and maximum shear stress were analysed to estimate the risk of failure in the models. In particular, Mises stress is relevant to ductile rupture of the materials. The maximum shear stress accounts for the slippage mechanism of fractures and it is incorporated in the Tresca effective stress $\sigma_T$ and it is evaluated as $\tau_{\text{max}} = \sigma_T/2$. The peak values of the normal and tangential stresses $\sigma_n$, and $\tau$ should be compared with the corresponding strengths of adhesion and cohesion at the interface between dentin and enamel.

Comparing the two different loading conditions, it was observed that in malocclusion the maximum value of both Mises and maximum shear stresses approximately doubled with respect to the ones in normal occlusion.

5. Conclusion

This paper proposes a new two-step procedure to identify damage in human premolar tooth by coupling image processing and stress analysis. More precisely, on one hand an efficient segmentation method was adopted to detect the reduction of the thickness of the enamel layer; on the other hand, the subsequent three-dimensional FEM analysis permitted to observe the variations of the stress distributions which occurred in normal occlusion compared with the malocclusion. The image analysis procedure provided a priori information to localize damage via automatic processing and
to direct FEM analysis and mechanical characterization just toward the identified zones.

It is apparent from the obtained results that the response of the structure was different if asymmetrical loading was considered. Significant weakening in the continuity of the structure of the hard dental tissues caused the increase of the stresses in the cervical region.

The results of the present study are in agreement with the observations in the literature [4,6,11,17–20] and provided an outlook in the biomechanical aspects related to the clinical developments of NCCLs.

**Conflicts of interest**

There is no conflict of interest.

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