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Elastic modulus of posts and the risk of root fracture

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Abstract – The definition of an optimal elastic modulus for a post is controversial. This work hypothesized that the influence of the posts' elastic modulus on dentin stress concentration is dependent on the load direction. The objective was to evaluate, using finite element analysis, the maximum principal stress (σ_{max}) on the root, using posts with different elastic modulus submitted to different loading directions. Nine 3D models were built, representing the dentin root, gutta-percha, a conical post and the cortical bone. The softwares used were: MSC.PATRAN2005r2 (preprocessing) and MSC.Marc2005r2 (processing). Load of 100 N was applied, varying the directions (0°, 45° and 90°) in relation to the post's long axis. The magnitude and direction of the σ_{max} were recorded. At the 45° and 90° loading, the highest values of σ_{max} were recorded for the lowest modulus posts, on the cervical region, with a direction that suggests debonding of the post. For the 0° loading, the highest values of σ_{max} were recorded for higher modulus posts, on the apical region, and the circumferential direction suggests vertical root fracture. The hypothesis was accepted: the effect of the elastic modulus on the magnitude and direction of the σ_{max} generated on the root was dependent on the loading direction.

Even though the techniques for restoring endodontically treated teeth were introduced several years ago, the procedure still remains a challenge in Dentistry (1–5). Additional difficulties arise as tooth structure is lost from the crown (6), since a direct restoration is unfeasible in such cases (2, 7), and intra-radicular posts are required to ensure retention of the indirect restoration (8).

The worst possible failure in such cases is vertical root fracture (9), which is usually irreparable. A combination of factors can make the structure prone to fracture, and two are noteworthy: (i) the substantially decreased structural integrity of the tooth because of the removal of tooth structure during endodontic access, dowel-preparation, and cavity preparation (10); (ii) stress concentration on the dentin because of the design or high elastic modulus of the post (11, 12).

The definition of an optimal elastic modulus for a post material is controversial. Some authors argue that the highest modulus material would be a better (13–17) fit for this situation while others propose the use of materials whose elastic modulus would match that of dentin (18–21). For a given geometry, the higher the modulus, the higher the stiffness. The stiffer post presents higher resistance to bending, therefore will go through less deformation when submitted to transversal loading (22). As a consequence, the root undergoes less strain as well, which reduces the risk of fracture. On the other hand, the stiffer post will have a more pronounced wedge effect (23), which increases the risk of fracture during longitudinal loading.

The hypothesis of this study is that the effect of elastic modulus on stress concentration may be dependent on load direction. Therefore, the conflicting results found in the literature may be explained by differences in the set-ups used in each study. The objective of this work was to evaluate the effect of the elastic modulus of the post material on maximum principal stress (σ_{max}) magnitude and direction using different loading directions, through finite element analysis.

Method and material

Nine three-dimensional models were built (Fig. 1), with 56440 hexahedrical elements (quad 8), in order to represent the root of a central incisor in the bone socket, restored with conical posts built with materials of three different elastic moduli (37, 100 and 200 GPa), submitted to loads of 100 N applied in various directions (0°, 45° and 90°) in relation to the post's long axis (Figs. 1 and 2). All structures simulated in the model were assumed to be isotropic, homogeneous and linear-elastic (elastic modulus and Poisson's ratio given in Table 1). Perfectly bonded interfaces were assumed. Total restraining of the degrees of freedom was imposed on the nodes at the upper section.

The programs MSC.Marc2005r2 (processing) and MSC/PATRAN2005r2 (pre- and postprocessing) were used. The magnitude of σ_{max} on dentin nodes in the A–D and E–H intervals of the plane section represented in Fig. 2 were compared, and the direction of the σ_{max} on the same planes were analyzed.

Results

Figure 3 represents σ_{max} values on the dentin as a function of the node position on the intervals A–D and

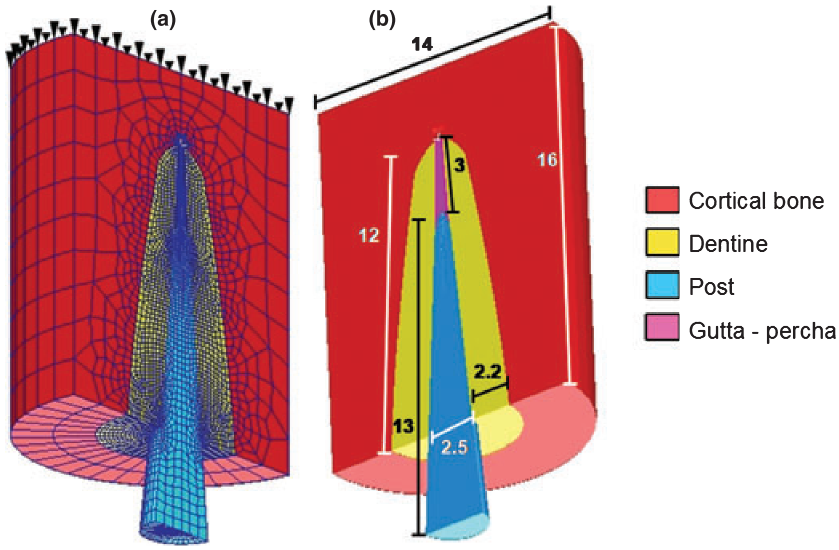

Fig. 1. Finite element 3D model. Half of the model (a) with the mesh and, (b) without the mesh. Dimensions in millimeter.

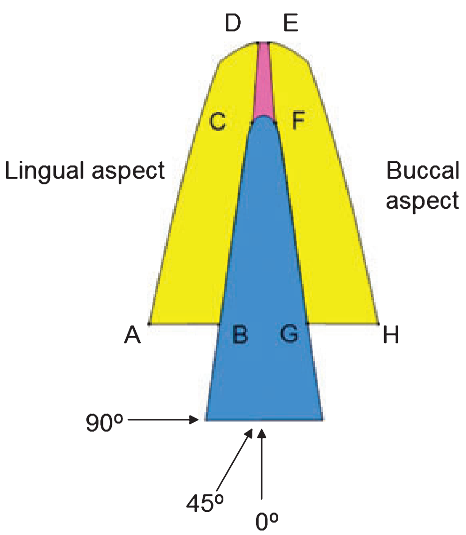

Fig. 2. Schematic representation of the intervals A–D and E–H, and of the loading direction (0°, 45°, and 90°).

Table 1. Elastic properties of the simulated materials

Material	Elastic modulus (GPa)	Poisson's ratio
Low stiffness (post)	37	0.30
Intermediate stiffness (post)	100	0.30
High stiffness (post)	200	0.30
Dentin (15)	18.6	0.31
Gutta-Percha (21)	6.9×10^{-4}	0.30
Cortical bone (21)	13.7	0.30

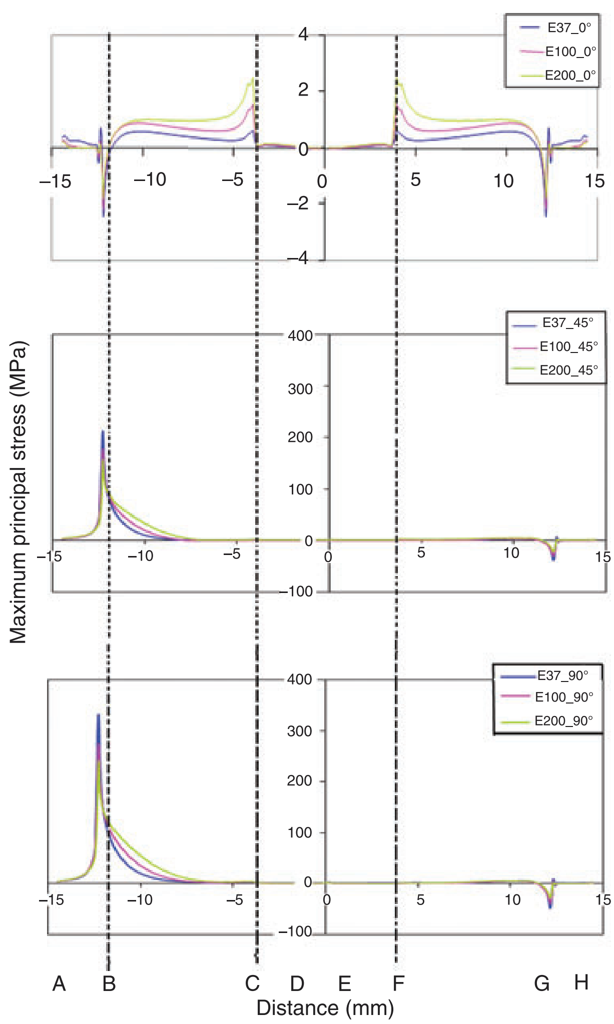

Fig. 3. Maximum principal stresses (MPa) in dentin as a function of node position on the intervals A–D, and E–H (given by the cumulative distance between contiguous nodes), for the different elastic modulus of the post (37, 100, and 200 GPa), grouped by loading orientation (0°, 45°, and 90°).

E–H (given by the cumulative distance between contiguous interface nodes), for the different models, grouped by loading direction. Table 2 compares the values on the stress peaks (points B, C, F and G). For the 45° and 90° loading, the highest $\sigma_{\max}$ values were recorded for the lowest elastic modulus posts and on the cervical lingual

Table 2. Maximum principal stress (MPa) on the dentin for the nodes located on points B, C and G as a function of the post's elastic modulus and loading direction

	Point B			Point C			Point F			Point G		
E (GPa)	0°	45°	90°	0°	45°	90°	0°	45°	90°	0°	45°	90°
37	−3.3	211.1	329.9	0.9	1.2	2.2	0.9	0.5	0.2	−3.3	−21.9	−27.6
100	−3	175.2	271	2	1.6	2.8	2	1.5	0.4	0.3	2.1	2.6
200	−2.6	154.3	238.2	3.1	2	3.1	3.1	2.4	0.7	0.2	1.1	1.4

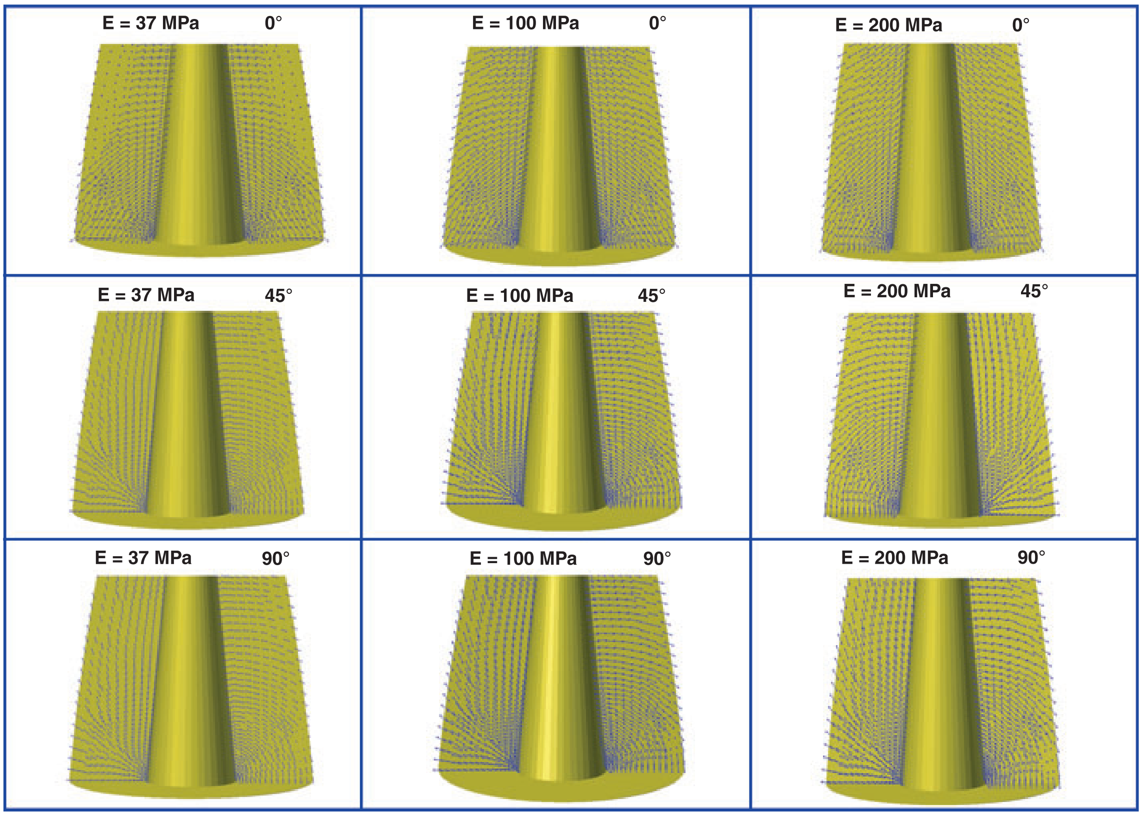

Fig. 4. Vectors direction on the maximum principal stresses on the cervical area.

area (point B). For the 0° loading, the highest values were recorded for the highest modulus post on the apical region (points C and F), although they were a 100 times lower than the ones obtained with the other loading directions.

Figures 4 and 5 represent the σ_{max} direction on the cervical and apical area, respectively, in a buccal-lingual plane. In the cervical region the vectors are on the represented plane, oblique to the root's long axis, while for the apical region it is possible to identify circumferential stresses, perpendicular to the represented plane, shown as small dots.

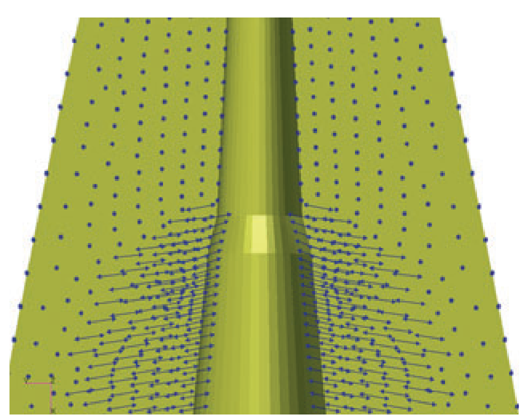

Fig. 5. Vectors direction for the maximum principal stresses on the apical area for the post with E = 37 MPa, and 0° loading.

Discussion

The hypothesis that the manner in which elastic modulus of the post affects tensile stress concentration in the dentin is dependent on loading direction was accepted. For the longitudinal loading (0°), the highest tensile stresses on dentin was observed with stiffer posts, which is in accordance with previous finite element studies that have used the same type of loading (21). The highest stresses occurred in the apical region (points C and F, Fig. 3). The circumferential direction of these stresses (Fig. 5) tends to force the root outwards, increasing its diameter, which could cause vertical fracture by wedge effect (24). In this case, the risk of root fracture would be expected to be higher for the stiffest posts (200 GPa), once the generated stresses are approximately 3.8 times higher compared to lower modulus posts (37 GPa). One explanation for that fact is that when a conical shaped post is forced into the root, the widest portion of the post (supposed to fit wider portions of the root canal) is compressed towards narrower regions. As a consequence, dentin walls are forced outwards and the root expands, generating circumferential tensile stresses (wedge effect). The higher the post's stiffness, the more noticeable this effect is, since stiffer materials are less deformable under the same load. However, when comparing the magnitude of stresses generated in the other loading directions (45° or 90°), there is a 100-fold decrease in stress, suggesting that in such cases the risk of fracture under longitudinal load is irrelevant, considering a perfect adhesion of the post to the dentin. Nevertheless, a perfect adhesion to dentin is very difficult to achieve and maintain in the clinical situation (25, 26). In such cases, the wedge effect may be relevant.

The literature points to fatigue mechanism as the primary cause of failures, which are essentially related to non-axial forces (5, 27, 28). Although axial loading is more frequent in posterior teeth, the stress that develops is of such low magnitude that fatigue is unlikely to happen. In turn, oblique and horizontal loading might lead to fatigue fracture even after only a few cycles, since the stresses generated by these force orientations are quite high. This fits with the present result.

For the oblique and horizontal loading, an inverse relationship between $\sigma_{\max}$ and elastic modulus was observed. Stress developed with less stiff posts was approximately 40% higher than the ones observed for stiffer posts. This is in agreement with previous studies (13, 16), in which a 45° loading was applied. In the oblique or horizontal loading, the post tends to bend with a fulcrum located at the cervical region. The lower the stiffness of the post, the more noticeable is the bending, which leads to higher elongation of the post on the side where the load is applied. As post and dentin were considered to be perfectly bonded, higher deformations in the post causes higher deformations on the dentin and consequently higher tensile stress. However, the site for stress concentration (cervical in the lingual aspect) and the stress direction (oblique to the long axis of the root, on the represented plane; Fig. 4) suggest a tendency for debonding of the post, instead of vertical fracture of the root. After adhesion failure, the post would be relatively mobile in the root canal and consequently would behave like a wedge (29). In this case, the root would become more prone to vertical fracture, as the stresses on the dentin are expected to increase considerably for non-bonded posts (5, 16).

Studies *in vitro* (30, 31) and *in vivo* (32) have shown a misleading disagreement with the present work as it was found by those authors that stiffer posts lead to less fracture resistance or higher *in vivo* rate of fracture. However, it was not the purpose of any of the previously mentioned studies to isolate the effect of the post's elastic modulus. In one of the *in vitro* evaluations (30), lower modulus posts were associated with the highest diameter. As the post's stiffness is a function of its elastic modulus and its geometry, it can be speculated that the results found by those authors would have been different had they used standardized geometries for all the posts. In the clinical trial and in the other *in vitro* study (31, 32), lower elastic modulus posts were adhesively luted with resin cements while higher elastic modulus posts were luted with a zinc phosphate cement. Previous studies (16) have already shown that adhesive luting leads to better stress distribution on the dentin, which potentially reduces the risk of root fracture. Also, the higher the bond strength between the post and the substrate, the higher the expected fracture toughness is for the root. Therefore, the luting system may have influenced the results in those studies.

As the effect of the elastic modulus on stress magnitude and distribution on the root depends on load direction, and this, in turn, depends on the tooth positioning in the arch (including possible malocclusion, e.g. bruxism), all these factors must be considered when choosing the post for each individual case. For posterior teeth, where the loads tend to be applied longitudinally, a lower modulus post luted with resin cements seems to be more appropriate. On the other hand, for incisors and canines, as these teeth are more subjected to oblique loading, stiffer posts appear to be the safest choice. It is noteworthy that other factors that fell outside the scope of this study have to be considered as well. For instance, aesthetic concerns, bond strength between the post and the substrate, root canal diameter, among others. As for the last item, it is well established that higher modulus materials require less preparation in the root canal to ensure enough posts' stiffness. A more flexible post may present more bending under loads, which may lead to failure or loss of the restoration (22).

It is important to notice that all this discussion applies to concentrical loading, in which no spinning takes place. Moreover, the model used in this study was simplified so to isolate the effects of the elastic modulus and loading direction and, for this reason, did not include neither the coronal portion of the post nor the crown or the periodontal ligament. This simplification simulates the worst case scenario, as stress reduction by the deformation of the ligament is excluded, and yet the general conclusions are not affected. Further studies are in progress in which the model will be completed, incorporating these elements and including cases in which an oval root canal is subjected to eccentric loading.

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