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Three-point bending testing of fibre posts: critical analysis by finite element analysis

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Abstract

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Aim To evaluate the effect of taper, specimen supports and the isotropic and orthotropic properties of the posts on flexure and stress response during three-point bending using finite element analysis.

Methodology A three-dimensional finite element model of a fibre post was created. The occlusal portion was cylindrical whilst the apical portion was tapered. Five different support positions were evaluated during a simulated three-point bending test: M1 – support distance of 10 mm centralized and no tilt; M2 – 10 mm centralized with tilt; M3 – 10 mm not centralized and no tilt; M4 – 10 mm not centralized with tilt; M5 – 6 mm not centralized with no tilt. A sixth post model (M6) was a centralized post without tapered section. The applied properties were elastic and orthotropic.

Results Tilting the tapered posts to level them in the test setup had little effect on the outcome. Flexure increased when 50% of the bent portion involved taper (M1, M2). If only 20% of the bent post involved taper (M3, M4), the flexure values were close to M6 (no taper). The orthotropic properties also caused increased flexure compared to an isotropic post. Maximum stresses were only a little higher when 50% of the bend structure involved taper, whilst the orthotropic properties had little effect.

Conclusions Regardless of levelling, the flexural stress determination with tapered fibre posts in the three-point bending test was valid as long as the tapered portion was limited in length.

Keywords: fibre post, finite element analysis, flexural properties, strength.

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Introduction

Non-metallic post systems have been used to restore root filled teeth. The stiffness behaviour of fibre posts is closer to dentine than metallic posts and has been an important motivation for their acceptance (Rosentritt *et al.* 2000, Santos-Filho *et al.* 2008, Santos *et al.* 2010).

Laboratory measurement of stiffness and strength properties for assessment and quality control of fibre posts is most often performed in flexural tests. Moreover, flexural properties are often considered an important indicator for the clinical performance of posts (Mannocci *et al.* 2001, Lassila *et al.* 2004, Galhano *et al.* 2005, Plotino *et al.* 2007). In flexural tests, posts are bent between three points, creating longitudinal tensile and compressive stress conditions. Tensile stresses are considered most critical, because they are most likely to initiate failure (Rodrigues *et al.* 2008). Flexural response is determined by the distance between the supports, post design and diameter (Drummond 2000, Mannocci *et al.* 2001, Lassila *et al.* 2004, Galhano *et al.* 2005, Grandini *et al.* 2005,

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Plotino *et al.* 2007, Seefeld *et al.* 2007). Since fibre posts come in different shapes (conical, cylindrical, cylindrical-conical), the stress distribution in posts and thus outcome of flexural tests is likely to be affected. Differences in diameter have been claimed to affect flexural strength, where thick posts return lower strength values than thin posts (Lassila *et al.* 2004). Variations in post geometry and span distance may be responsible for differences between data reported in flexural test studies (Drummond 2000, Mannocci *et al.* 2001, Lassila *et al.* 2004, Galhano *et al.* 2005, Grandini *et al.* 2005, Valandro *et al.* 2006, Plotino *et al.* 2007, Seefeld *et al.* 2007, Novais *et al.* 2009). Thus, standardization of flexural tests for non-metallic posts may be needed. Designing a universal standard, however, is complicated because posts, which often feature partial taper, cannot be easily adapted to strict geometrical standards.

The aim of this study was to evaluate the stress and deformation in various fibre post designs to create insight into the biomechanical behaviour during bending tests. Finite element analysis (FEA) was used, which is a versatile tool to test interactions between physical factors (Soares *et al.* 2008). Test design parameters such as distance between supports and post orientation were varied to test the null hypothesis that they do not affect the maximum stress in the posts.

Materials and methods

Flexure and stress distributions in fibreglass posts were evaluated during three-point bending for various testing conditions using FEA (MSC.Marc; MSC.Software Corporation, Santa Ana, CA, USA). Configuring the FEA comprised of creating the geometrical models, assignment of material properties, and prescribing loading and support conditions.

The three-dimensional (3D) finite element model of the post was generated based on the dimensions of a Relyx Fiber Post (3M-ESPE, Seefeld, Germany). The total length of the post was 20 mm, where the 10 mm coronal portion was cylindrical (1.9 mm diameter) and the 10 mm apical portion tapered (apical end 0.893 mm diameter). The fibreglass model mesh consisted of 8 node hexahedral elements.

The fibreglass post was considered homogeneous, linear-elastic and orthotropic. Mechanical properties were obtained from the literature (Asmussen *et al.* 1999, De Santis *et al.* 2000, Ferrari *et al.* 2000). The longitudinal *z*-direction was the principal direction; *x*- and *y*-directions indicate the perpendicular directions. The elastic modulus in longitudinal direction Ez was 37.0 GPa; Ex and Ey in the perpendicular directions were 9.5 GPa. The Poisson's ratios ηzx, ηxy and ηyz in the orthogonal planes (zx, xy and yz) were 0.27, 0.34 and 0.27, respectively. The shear moduli Gzx, Gxy and Gyz were 3.1, 3.5 and 3.1 GPa, respectively.

The posts were bent between three supports, modelled as rigid contact bodies (2.5 mm diameter). The two lower supports were fixed. The upper support, on which the flexural load was applied, was only allowed to move along the vertical load axis. Friction between post and supports was considered negligible. Five different testing conditions were simulated with regard to the support span and position, and tilt of the post (Fig. 1):

- Model 1 (M1): 10 mm span distance between lower supports with post centered (both cylindrical and tapered portions loaded) and horizontal;
- Model 2 (M2): 10 mm span distance between lower supports with post centered (both cylindrical and tapered portions loaded) and tilted;

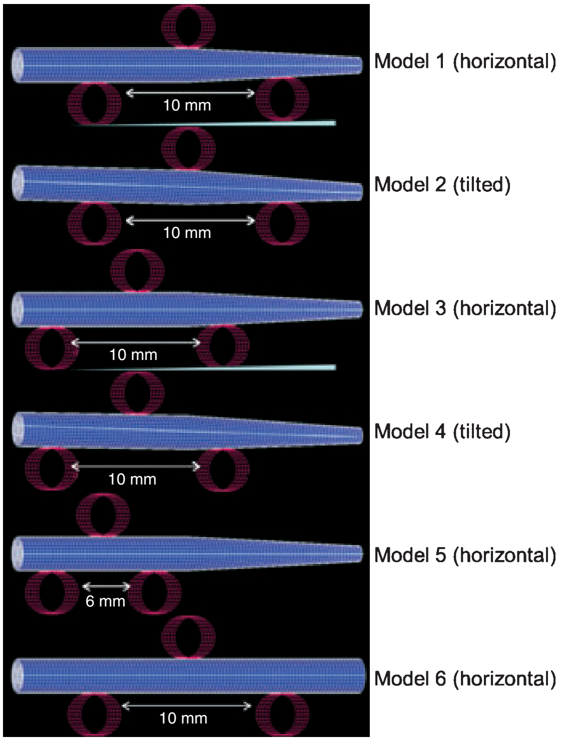

Figure 1 Schematic illustration of 3D-models of the simulated three-point bending tests, showing the different placements, support distances and tilts.

- Model 3 (M3): 10 mm span distance between lower supports with post positioned off-centre and horizontal;
- Model 4 (M4): 10 mm span distance between lower supports with post positioned off-centre and tilted;
- Model 5 (M5): 6 mm span distance between lower supports with post positioned off-centre (only cylindrical portion loaded) and horizontal.

Additionally, a post without a tapered portion (Model 6) was evaluated as a reference, both for orthotropic (M6) and isotropic properties (M6-iso). Furthermore, analytical flexure and stress solutions were calculated for a 1.9 mm diameter post using the regular engineering bending theory expression for 6 mm or 10 mm support distances, A6 and A10, respectively.

Displacement at the load application point and the maximum tensile stress in the post were calculated and recorded during simulated flexural loading.

Results

Force–displacement curves plot the relation between the bending load during flexure and the displacement of the centre of the posts (Fig. 2). Tilting specimens had little effect on flexure values (M1 and M2; M3 and M4). Changing the placement of posts on the supports changed the curves. Placing more of the tapered portion between the supports (M1, M2) increased flexure compared to cases where less taper was involved (M3, M4). Flexure of the untapered model (M6) was close to the M3 and M4 values. Reducing support span decreased flexure (M5). Flexure of the orthotropic post (M6) was higher than of the isotropic post (M6-iso).

Force–stress curves plot the relation between the bending load during flexure and the maximum tensile stresses found at the bottom of the posts (Fig. 3). Tilting specimens did not have much effect on flexure stress values (M1 and M2; M3 and M4). Placing more of the tapered portion between the supports (M1, M2) caused only a small increase in flexure stress compared to the cases where no or less taper was involved (M3, M4, M6). Reducing support span decreased flexure stress under the same bending load (M5). Maximum flexural stress values in the orthotropic and isotropic posts were nearly identical (M6 and M6-iso).

Discussion

Flexural tests have been used to determine stiffness and strength of non-metallic post systems (Torbjörner *et al.* 1996, Lassila *et al.* 2004, Grandini *et al.* 2005, Valandro *et al.* 2006, Novais *et al.* 2009). The International Organization for Standardization (IOS) has developed specifications for three-point bending tests of polymer-based materials (IOS). These specify rectangular or circular specimen cross-sections to be bent under a compressive loading applied at equal distance between two supports. The tensile stresses that this bending generates in the specimen have been associated with failure initiation (Rodrigues *et al.* 2008). Since no specific standard exists for materials reinforced with

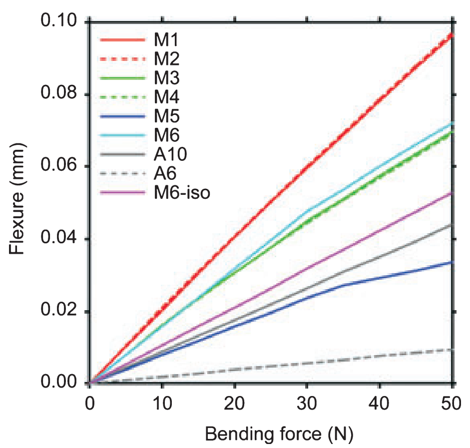

Figure 2 Force–displacement curves for the six bending models. The flexure was determined at the load application point. Also shown are the analytical curves for a cylindrical beam calculated for 6 and 10 mm support span distances (diameter 1.9 mm).

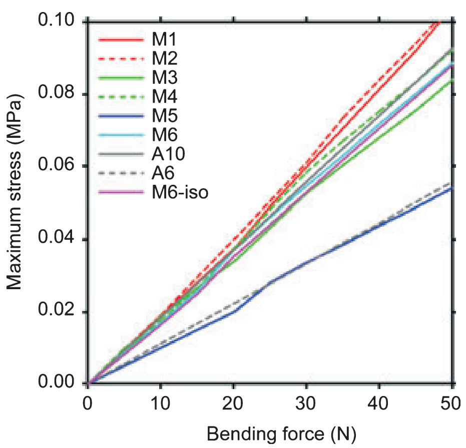

Figure 3 Force–stress curves for the six bending models. The stress was the maximum flexural stress found at the bottom of the beams. Also shown are the analytical curves for a cylindrical beam calculated for 6 and 10 mm support span distances (diameter 1.9 mm).

fibre, non-metallic posts are often tested using the same bending setup as specified for polymer-based materials. Maximum tensile stress σ_{max} is subsequently calculated using the engineering bending theory expression:

$$\sigma_{max} = 8F_{max}l/\pi d^3 \quad (1)$$

where F_{max} is maximum applied load, l is distance between the supports (span) and d is diameter (Torbjörner *et al.* 1996, Lassila *et al.* 2004, Grandini *et al.* 2005, Valandro *et al.* 2006). Fibre posts, however, differ from the IOS-standard specimens because of their tapered sections and reinforcing fibres. The objective of this study was to investigate and discuss the complications and validity of using three-point bending experiments for testing of fibre posts.

The first practical concern when using fibre posts in three-point bending tests is that many have a tapered section. How should tapered specimens be placed on the supports? Should they be levelled? The results of the current analysis show that levelling the posts had little effect on flexure and maximum stress values.

A tapered section also raises concerns about the validity of using expression (1) for calculation of maximum stresses. The expression assumes a prismatic beam (constant cross-section), and will become inaccurate for large deflections (supports too far apart), interference of the support areas (supports too close together and/or support diameter too large), or if the material is not homogeneous. In this study the maximum stress and flexure values were calculated using FEA because, unlike expression (1), FEA can take the tapered shape and orthotropic properties into account and allows a systematic investigation of experimental variables (Versluis *et al.* 2006).

By varying the position of the supports, the analysis revealed that the effect of taper on flexure can be substantial. If half the span involved taper (M1 and M2), flexure increased substantially compared to the untapered post (M6). However, when only 20% of the span involved taper (M3 and M4), the effect on flexure was not substantial. The corresponding maximum stress values showed a similar, although less pronounced trend. The larger effect of taper on flexure could be expected considering its expression according to the engineering bending theory:

$$v = 4Fl^3/3E\pi d^4 \quad (2)$$

where v is flexure and E is elastic modulus. The higher order diameter term in (2) compared to (1) indicates a higher sensitivity to diameter changes for flexure than for the maximum stress.

Unlike the expressions (1) and (2), which assume a constant cross-section and isotropic properties, FEA calculated flexure and stresses in the posts with their actual geometry and property. Comparison between engineering bending theory and FEA shows a large difference for the flexure values whilst the maximum stress values are relatively close. Differences between flexure values can be largely attributed to the orthotropic properties. This was verified by applying isotropic properties, showing that the difference between the flexure outcomes of the two calculations narrowed (M6-iso). Post flexure is thus affected by properties in all dimensions. On the other hand, stress, which expresses how a force is distributed through a body, is determined by force-moments and cross-sectional areas. Stress values were less affected by the material properties (isotropic/orthotropic), hence the similar values obtained by the engineering bending theory and FEA.

Besides taper and properties, span distance also affects flexure and stresses because of associated bending displacement and interference of supports. When a beam flexes, its contacts change, effectively reducing span distance and even potentially affecting loading locations. In this analysis two span distances (10 mm and 6 mm) were modelled. The 6 mm span was chosen to explore if the test could be achieved on the cylindrical section alone, avoiding the complications posed by the tapered section. The analysis showed that flexure increase reduced for bending loads above 30 N for the model with 10 mm span (M6), visible as a reduction in the inclination of the force-flexure curve. For the 6 mm span (M5) the flexure increase reduced above 35 N. The observed reduction could be explained by the decrease in support distance at higher flexure values, and thus stiffer beam response. A slight increase in maximum stress value was observed above 15 N for the 10 mm span (M6) and above 20 N for the 6 mm span (M5). This increase in longitudinal tensile stress may have been the effect of the combination of flexure and friction with the immovable support positions, neither of which is taken into account in the engineering beam theory or IOS standards. However, disregarding these flexural effects, overall results for the 6 mm span (M5) were consistent with the general assessment of a common 10 mm span test design (M6), and the maximum stress in the 6 mm span obtained by the engineering bending expression can be expected to be close to the outcome of the FEA.

It thus appears that maximum stress values for fibreglass posts are acceptable using methodology similar to the IOS standards for polymer materials, provided that the taper between the supports is minimized. IOS methodology for elastic modulus determination should not be used because the flexure calculation in expression (2) is not accurate for tapered sections and non-isotropic materials.

The above assessments assumed a homogeneous distribution of material properties in the posts. Although fibres and resin matrix components may be uniformly distributed, they have different properties. In this study, fibres and matrix were not modelled separately. Instead, resultant stiffness properties of the FRC material were applied. Therefore, the calculated bending behaviour of the FRC post can be expected to be close to reality. Stresses, however, may be locally elevated due to interfacial concentrations. Calculated maximum stresses should be viewed as homogenized values of the whole post responding as one material, and should not be associated directly with the ultimate fibre or matrix strength.

The results of this study support flexural strength testing of fibreglass posts as an appropriate procedure for quality control. However, clinically, post strength is probably not a major concern because they hardly ever fracture. The mechanical significance of clinical application of fibreglass posts is their reduced stiffness in comparison with metallic post. The resultant elastic modulus of fibreglass posts is closer to dentine, which has been shown to provide more beneficial stress distributions in the tooth structure (Santos-Filho *et al.* 2008, Soares *et al.* 2008). It can be argued that measuring flexure to determine elastic modulus of the post is clinically more important than flexural strength. Unfortunately, this study suggests that taper is a larger obstacle in flexure measurements than it is for maximum stress determination.

Conclusion

Three-point bending tests can be used to determine flexural strength of fibre posts, even when they involve some taper. Tilting the specimens to level the posts is not necessary. Errors due to taper and amount of nonlinear flexure were relatively small, and can be reduced by limiting the taper in the tested section. Flexural strength values determined using expression (1) can be considered a property of a fibreglass post, assuming fibres and matrix respond as one homogeneous material. If taper is less than 50% of the span, the largest diameter value can be applied in the maximum stress calculation. Differences in post diameter between manufacturers should not be a limitation, because the strength property should be independent of post diameter if errors due to taper and flexure are minimized. Standardizing exact post or support dimensions is therefore less useful than standardizing the relationship between post diameter, support span, diameter of supports, and the maximum allowable flexure. To further improve accuracy, error corrections for taper can be developed by FEA.

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