DENTAL-1074; No. of Pages 8 ARTICLE IN PRESS

dental materials xxx (2007) xxx–xxx

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.intl.elsevierhealth.com/journals/dema

Rotational fatigue-resistance of seven post types anchored on natural teeth

H.W. Anselm Wiskott, Malika Meyer, Jean Perriard, Susanne S. Scherrer*

Department of Prosthodontics-Biomaterials, School of Dental Medicine, University of Geneva, 19, rue Barthélemy-Menn, 1205 Geneva, Switzerland

ARTICLE INFO

Article history:
Received 28 July 2006
Accepted 6 December 2006

Keywords:
Post
Buildup
Fatigue
Failure

ABSTRACT

Purpose. To develop a laboratory model aimed at duplicating the failure process of post and core restorations. The load pattern applied was to be repetitive (fatigue) and multivectorial. To determine and compare the resistance under fatigue loading of seven endodontic post/natural root combinations: stainless steel-, titanium-, ceramic-, composite-fiber/epoxy-, two glass-fiber/epoxy- and glass-fiber/acrylic posts.

Materials and methods. The repetitive, alternating and multivectorial intraoral force pattern was reproduced by subjecting the specimens to the rotating cantilever beam test. To this end, the samples were designed as rotation-symmetric structures comprising a root, a post, periodontal ligament- and bone analogs and a restoration analog. The following posts were tested: Unimetric-Ti, Unimetric-SS, Biopost, Composipost, Easypost, DT Lightpost, Everstick-post. The samples were spun around their long axes while being clamped into a revolving collet on one end and loaded normal to their long axis on the other end. The aim was to determine the load level at which 50% of the specimens survived- and 50% fractured before 10E6 cycles. The 50% means were determined using the staircase procedure.

Results. In increasing order of magnitude, the resistances to fatigue loading were as follows: Biopost, Unimetric-Ti, Unimetric-SS, Composipost, Easypost, Everstickpost, DT Lightpost.

Significance. The fatigue resistance of the two fibrous posts with the highest fatigue resistance was twice that of any of the ceramic or metal posts.

1. Introduction

To serve as abutments for full-coverage restorations, severely damaged teeth must have their clinical crowns restored. These reconstructions are often secured to the root using endodontic posts [1]. For years, such dowels were machined or cast out of metal. More recently, ceramics [2] and fibrous [3,4] composites were introduced. These developments prompted enquiries geared at determining whether one doweling system could claim superiority over the others. In this context, two issues were at stake: (1) the anchorage capacity of the post and (2) the damage to- and the retrievability of the root after the post either lost retention or fractured.

Both concerns were addressed in a number of in-vitro and in-vivo studies. Comparative clinical studies however, are scarce; therefore the relative durability of the systems must be inferred by comparing long-term survival rates of metal- [5–10], fiber- [11–13] and ceramic [14] posts.

Only seldom do restorations break under monotonic load application. The typical mechanical failure of intraoral structures is attributable to fatigue processes [15]. It is also established that the teeth are subjected to arrays of mostly

* *Corresponding author*. Tel.: +41 22 382 91 73; fax: +41 22 382 91 73.
E-mail address: anselm@wiskott.com (H.W.A. Wiskott).

0109-5641/$ – see front matter © 2006 Academy of Dental Materials. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.dental.2006.12.001

oblique loads [16,17]. These force vectors, therefore, have both a vertical (i.e. along the tooth's long axis) and a horizontal (i.e. normal to the axis) component. A laboratory test aimed at evaluating the mechanical resistance of structural components should therefore duplicate both the repetitive and the multivectorial nature of introral force application.

To a large extent, rotating beam tests satisfy both requirements. In these tests, revolving rod-shaped specimens are stabilized on both ends via ball-bearings while they are loaded normal to their axis of rotation in their mid-portion. When the beam is rotated 180°, the stresses in the fibers originally below the neutral axis are reversed from tension to compression and vice versa. When the flexural cycle is completed the stresses are again reversed to the original state. In endurance tests, the mid-portion of the specimens are hence subjected to continuously alternating phases of tension and compression. Cyclic loading procedures were originally devised by Wöhler during the development of new fatigue-resistant alloys for railroad stock [18] and later adapted to other industrial applications using "R.R. Moore machines" [19]. In a simplified version, the rotation-bending principle applies equally well to the testing of dental components. To this end, the components are designed as rotation-symmetric samples, which are gripped in a rotating collet on one end and subjected to a load normal to the axis of rotation on the other. The samples are therefore subjected to alternating fields of tensile and compressive stresses. Such rotating cantilever beam tests have been applied in investigations on the fatigue resistance of prosthodontic structures [20–22], alloys and solderjoints [23], resinous materials [24] and adhesive interfaces [25].

In view of the poor discriminating potential of clinical research regarding the comparison of metal-, fibrous- and ceramic post systems, it was decided to approach the problem by applying the rotating-bending principle. The objective of the present project therefore was to closely duplicate intraoral loading conditions in a laboratory test designed to compare the resistance to fatigue loading of seven endodontic post/natural root combinations: stainless steel-, titanium-, ceramic-, composite-fiber/epoxy-, two glass-fiber/epoxy- and glass-fiber/acrylic posts. In addition, the mode of failure (structural failure of the post, loosening of the post, root fracture) was also recorded.

2. Materials and methods

2.1. Overview

Samples that comprised a bone- and a periodontal ligament analog, a root, a post and an abutment analog were configured as rotation-symmetric specimens. Applying the rotating-bending principle, the samples' inner ends (i.e. the bone analogs) were secured to a lathe-type collet and the protruding ends (i.e. the restoration analogs) were loaded normal to the axis of rotation via a ball-bearing. While rotating, the specimens were thus subjected to extended periods of sinusoidal tension–compression cycles. By progressively increasing the load applied, the goal of the experiment was to determine the load level at which 50% of the specimens survived 10^6 cycles and 50% failed. Each sample was spun at 1000 rpm and thus required about 17 h of testing.

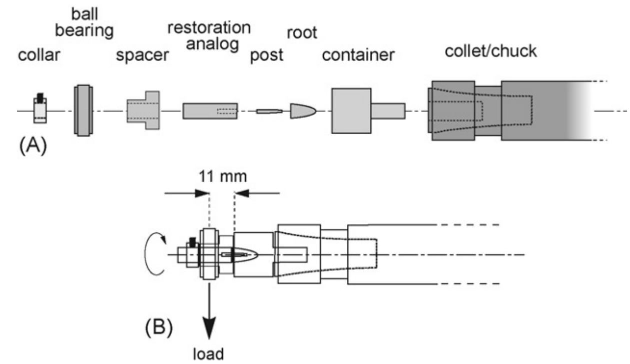

Fig. 1 – Principle of rotating beam fatigue test. The container housing the bone analog (i.e. a resin) is clamped into a collet and rotated. The root and the post are collinear with the axis of rotation. An aluminum tube serves as abutment analog. It is secured to the post head and dimensioned so that a ball-bearing can be affixed to the protruding end. After loading the ball-bearing, this generates cycles of tension and compression inside the post, the cement and the root thereby fatiguing the structures and leading to their final breakage. The lever acting between the emergence of the root from the bone analog and the point of force application was kept constant at 11 mm using a spacer.

The principle of rotation-bending tests requires that all component of the system (i.e. the grips, the specimens and the ball-bearings) be collinear and that the length of the lever acting between the outer support of the tooth and the point of force application be kept constant (Fig. 1).

Technical aspects of the machinery and ancillary controls were described in previous reports [26,27].

2.2. Test groups

The objective of the study was to determine whether specific combinations of posts and cementation procedures were more resistant to fatigue loading than others. To this effect, the following pairs were selected for investigation: machined metal posts (stainless steel, titanium) cemented using glass ionomer cement, ceramic posts using an adhesive technique, fibrous posts (carbon-fiber/epoxy, glass-fiber/epoxy, glass-fiber/acrylic) using an adhesive procedure. Besides availability, a minimum seating length of 8 mm and a diameter at the emergence of the root of 1.35 ± 0.15 mm were the criteria for inclusion of the post brands into the study. The specifics of each group are detailed in Table 1. Each post's housing was prepared with the system's proprietary burs. The housing for the Everstick post was prepared using the Biopost's burs.

In the non-adhesive procedure, the posts were cemented using glass-ionomer cement (Ketac-Cem, 3M-ESPE). For the adhesive technique, the housing's dentinal surface was first infiltrated with self-etching primer (A.R.T. Bond system, Coltene). Then the bonding resin was applied and the posts luted using a resin-based cement (Variolink, Vivadent).

Please cite this article in press as: Wiskott HWA, et al., Rotational fatigue-resistance of seven post types anchored on natural teeth, Dental Mater (2007), doi:10.1016/j.dental.2006.12.001

Table 1 – Specifications of the posts used

Denomination	Material	Geometry	Diameter (mm)	Surface texture	Cementation non-adhesive/ adhesive	Manufacturer/ reference
Unimetric-Ti	Titanium Ti6Al4V	Conical 5° taper	1.45	Serrated	Glass-ionomer	Maillefer
Unimetric-SS	Stainless steel DIN 1.4305	Conical 5° taper	1.45	Serrated	Glass-ionomer	Maillefer
Biopost	Zirconium oxides Y-TZP	Cylindrical-conical	1.5	Smooth	Adhesive	Incermed BP02L
Composipost	Carbon fibers (64 vol.%) epoxy resin (36 vol%)	Two-staged cylindrical	1.4	Smooth	Adhesive	RDT
Everstick post	E-glass fibers unpolymerized acrylic composite matrix	N/A	Ca. 1.5	N/A	Adhesive	Stick Tech
Easypost	Si–Zr fibers (60 vol.%) epoxy matrix (40 vol.%)	Cylindrical-conical	1.35	Smooth	Adhesive	Maillefer
DT Lightpost	Quartz fibers (60 vol.%) epoxy resin (40 vol.%)	Cylindrical-conical	1.25	Smooth	Adhesive (adhesion to MMA via priming layer)	RDT

2.3. *Specimen preparation*

Designing the samples for the present experiment proved to be a tedious procedure. Indeed, it was of importance to securely grip the teeth carrying the posts while still leaving the roots some leeway for breakage (as in natural conditions) that is not encasing them in direct contact with a polymer matrix. The conundrum was solved by sheathing the roots with a thin hose of polyethylene and attaching the apices to their container using multistand stainless steel cable as described below.

The teeth from which the roots were prepared were chosen so as to fit the following specifications: at least one third of the clinical crown remaining, absence of intrinsic staining or crazes, a uniformly convex root section, a diameter of 6 ± 1 mm at the cementoenamel (CEJ) junction. If the teeth were slightly too large, any excess in width within approximately 1 mm was gently sanded off the root's surface. The root length was adjusted to 14 mm by first trimming the coronal- and then the apical aspects of the roots.

A diagrammatic view of the specimens is shown in Fig. 2. The container housing the bone analogs were 18 mm × 18 mm stainless steel cylinders configured with shafts that fitted into the machine's collet. The roots were surrounded with a polyethylene hose that was lightly heated before pulling it over the teeth. After cooling, its thickness was 0.2–0.4 mm and it could therefore function as a periodontal ligament analog [28]. The bone structure was duplicated by encasing the roots into selfpolymerizing resin. To prevent the teeth from escaping from their housing, a piece of multistrand cable was adhesively fastened to the apices of the roots. The cable was reeved through the shaft and, after light pulling, was screw-tightened to the container.

On the protruding end, the crown analogs were fabricated using 6 mm diameter aluminum rods. On their inner end, the rods featured a recess that was large enough to accommodate the posts' heads and the rods could thus be cemented onto the posts using selfpolymerizing composite resin (Variolink, Vivadent).

The rotating beam principle required that the posts were located on the axis of rotation. This was achieved by utilizing a paralleling frame made of two cylindrical steel rods seated in aluminium blocks on each end. A third aluminium block was fitted with brass gliders and could move freely inside the frame on the steel rods. This device has been described in more detail elsewhere [27]. The specimen fabrication technique consisted in first centering the post on the axis of rotation using a "mock" post for which a 8 mm deep recess had been prepared by enlarging the root's pulpal canal. After the root had been fitted with a multistrand cable wire on its apex and sheathed with the polyethylene hose, the mock post was inserted into

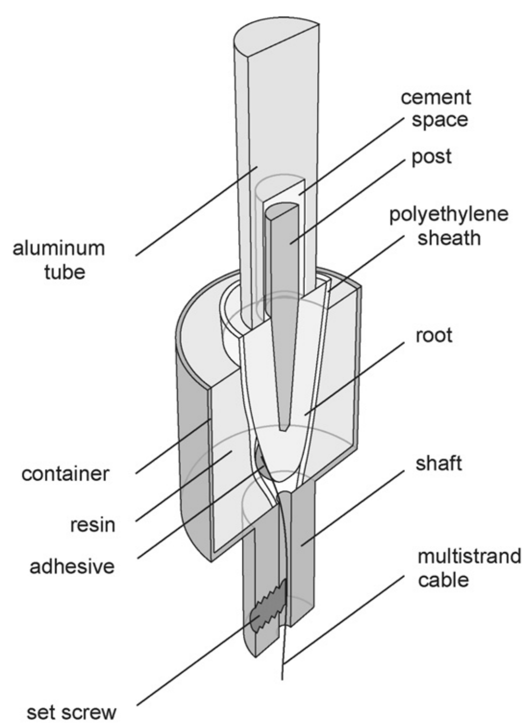

Fig. 2 – Schematics of the specimens. The root was sheathed into a polyethylene hose and encased into resin (i.e. the bone analog). The resin was housed in a container featuring a shaft to be griped into a rotating collet. The root was prevented from escaping its resin housing by a multistrand cable that was crew-fastened to the shaft. An aluminum tube that was cemented onto the post's head served as crown analog.

the root's housing and its protruding end was gripped into the collet that was affixed to the frame's movable block. Then the containers were secured to the opposing frame's fixed bar and the root was gently lowered into the container while threading the multistrand wire through the shaft's canal. Last the resin (i.e. the bone analog) (Technovit, Heraeus-Kulzer) was poured into the container leaving 2 mm of root exposed. After setting of the resin and removal from the frame, the set screw in the shaft was tightened onto the wire.

The final shape of the post housing was produced at this time and the posts were cemented according to the protocols described above. The apical ends of the root canals were prepared up to a #30 reamer but were not filled.

2.4. *Experimental procedure and data analysis*

For testing, the length of the lever acting on the post (i.e. the distance between the emergence of the root from the bone analog and the midpoint of the ball-bearing) was kept constant at 11 mm. This figure has no specific meaning in the present experiment but was established to allow comparisons with previous studies [29]. The sole differences between groups, therefore, were the variations in post materials and cementing agents. The slight deviations in root dimensions and dentin structure were considered random and evenly distributed between the groups.

The fatigue resistance of each post-cement-root combination was determined using a technique known as "staircase-" or "up-and-down" analysis [30,31]. The technique requires that a number of specimens be tested in sequence and consists in determining a mean load level at which 50% of the samples survive 10^6 load applications and 50% fail (this level will be termed F_{50}). To this end, a first sample was cycled for 10^6 rotations at a given load (F). After 10^6 cycles, the test was halted and it was determined whether the sample had broken or whether it had survived 10^6 cycles without breakage. If the sample was a 'runout' (no breakage) a new sample was cycled for 10^6 cycles at a level F plus a predetermined force increment (F_{incr}). If the previous sample had failed, the new sample was tested at $F - F_{incr}$. This leads to the characteristic up-and-down pattern of runouts and failures that gives its name to the procedure. When applying the staircase technique, two issues need to be considered. First, the experimentalist must set an appropriate F_{incr}. If it is too large, the test looses its discriminating potential. Conversely, setting F_{incr} too low unduly increases the number of specimens. Second, the test must evolve in an up-and-down pattern. Portions of the sequence in which the data are only ascending (or descending) may not be included into final analysis. The number of specimens in the sequence was set as follows. Specimens were tested in sets of five and the up-and-down pattern was deemed acceptable when five reversals were obtained. Sets of five samples were added until this condition was satisfied.

During testing, the results were graphically charted as in Fig. 3. After all tests were completed, they were arranged as shown in Table 2. Taking A and B from Table 2, F_{50} was calculated as

$$F_{50} = F_0 + F_{incr}\left[\frac{A}{n} \pm \frac{1}{2}\right]$$

(+ : if the test is based on runouts,

− : if the test is based on failures)

Whenever the number of run-outs and failures differed, data analysis was based on the least frequent event.

The corresponding standard deviation was taken as:

$$\text{S.D.} = \begin{cases} 1.62F_{incr}\left[\dfrac{nB - A^2}{n^2} + 0.029\right] & \text{if } \dfrac{nB - A^2}{n^2} \geq 0.3 \\ 1.53F_{incr} & \text{if } \dfrac{nB - A^2}{n^2} < 0.3 \end{cases}$$

with F_{50} the mean force level at which 50% of specimens run-out and 50% fail; F_0 the lowest load level at which failure occurred; F_{incr} the chosen force in/decrement: 2.5 N; n the $\sum n_i$ (n_i is the number of failures for each load level) (see Table 2); A the $\sum in_i$ (i: load level); B the $\sum i^2 n_i$.

To assess whether the F_{50}'s of each group were significantly different, the means were fitted with 95% confidence intervals using a method described by Collins [32]. Means with overlapping intervals were considered equivalent.

In excess of 150 specimens were produced during the course of the experiment (while only 125 were actually part of the test sequences). First, a number of "non-productive" samples were required for calibration. Calibration was necessary to ensure that the model worked properly that is excluding failure modes other than those that reproduced a clinically pertinent event. Second, the initial samples of each sequence usually turned out empty, that is, they were set too low to be part in the up-and-down reversal pattern that typifies the staircase procedure and therefore were not included in the

Table 2 – Example of data arrangement for staircase analysis (Everstick posts)

Applied force (N)	Force level (i)	Number of failures (n_i)	in_i	$i^2 n_i$
27.5	4	3	12	48
25	3	2	6	18
22.5	2	1	2	4
20	1	1	1	1
17.5	0	1	0	0
		$n = 8$	$A = 21$	$B = 71$

With $n = \sum n_i$, $A = \sum in_i$; $B = \sum i^2 n_i$.

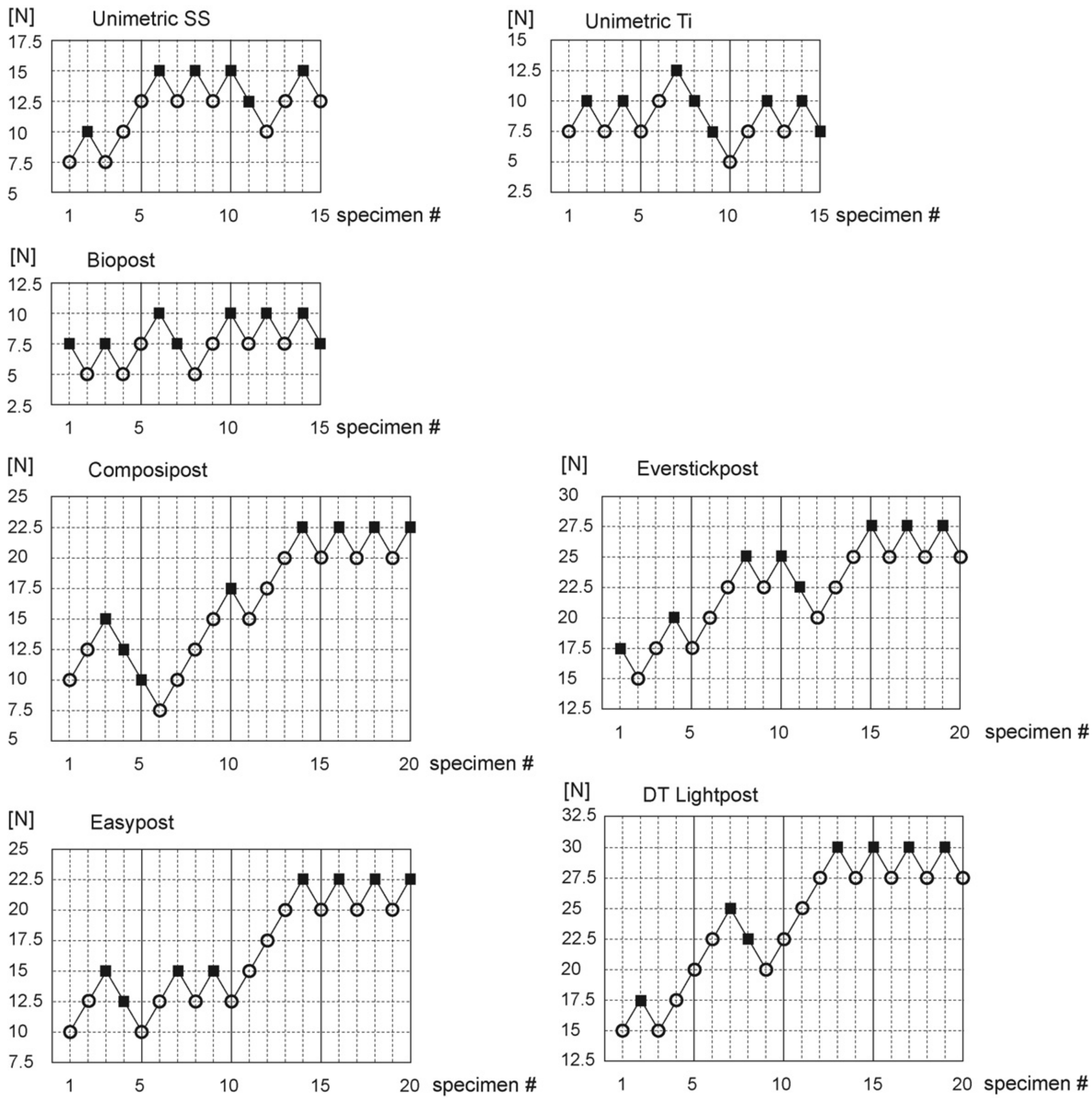

Fig. 3 – Staircase data for the post-cement combinations investigated. The number of specimens in each series was increased in sets of five until five reversals were observed. This required 15 specimens for the ceramic and metal posts groups and 20 for the fibrous posts groups.

calculations. Third in 8 instances, the multistrand cable either broke or loosened from the root. These specimens were discarded and new specimens were used.

3. Results

3.1. *Fatigue strength*

The pattern of runouts and failures for each post-cement combination is depicted in Fig. 3. The calculated means at which 50% of the samples survive 10^6 cycles and 50% fail as well as their 95% confidence intervals are presented in Fig. 4. In Fig. 4 two sets of results are shown. The first (termed "full set") includes all valid data generated for each combination during the course of the experiment (a 'valid' datum is one that lies within the upper and lower boundary of the pattern of reversals produced during the sequence). The second set includes only the 10 last data of each sequence. Indeed, when observing the evolution of the data in the sequences, the fibrous posts initially presented a fairly large variability and then their up-and-down pattern steadied. As it includes only the 10 last samples of each sequence, the second set describes the pattern once it has stabilized. In contrast, the full data set accounts for the entire variability of the results (in terms of each F_{50}'s confidence intervals).

The above has obvious implications in terms of statistical interpretation. When taking the full set into consideration, only few of the groups diverge. Conversely, when only the 10 last samples are considered, all groups are statistically different with the exception of the Composipost-Easypost and Biopost-Unimetric-Ti groups.

Please cite this article in press as: Wiskott HWA, et al., Rotational fatigue-resistance of seven post types anchored on natural teeth, Dental Mater (2007), doi:10.1016/j.dental.2006.12.001

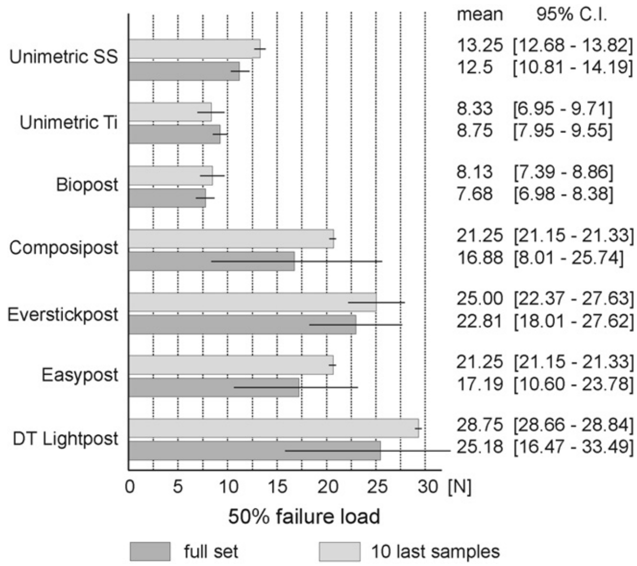

Fig. 4 – Mean and 95% confidence intervals of the post-cement combinations tested. Results are given for the full data set (15, respectively 20 samples) and for a subset comprising only the last 10 samples of each series. Note the important decrease in standard deviation when only the last 10 samples are considered.

3.2. *Failure modes*

None of the ceramic and metal posts (Biopost, Unimetric-Ti, Unimetric-SS) fractured; in three (out of 22 instances) the root broke during the failure process. The Composiposts failed either by fracturing (three out of eight) or by decementation (five out of eight). The remaining fibrous posts (Easypost, Everstickpost, DT Lightpost) mostly failed by delamination, that is, the posts lost their integrity and split longitudinally. Three out of eight Easyposts decemented. In three out of 23 instances the root fractured.

4. Discussion

4.1. *Rotational fatigue testing*

Subjecting dental components to rotational fatigue loading instead of testing them using actuator driven machines [33,34] may at first glance appear at odds with clinical force application. However, spinning the specimens as in the present setup will to a large extent duplicate the multivectorial nature of intraoral force application [16,17]. Further, rotational fatigue is a test that calibrates itself onto the 'weakest' location of the circumference. (In the present context, 'weak' is a colloquialism expressing the highest stress concentration that each part of the structure can sustain without cracks opening in its outer layer or in the subsurface [35]). Actuator-driven machines will not calibrate themselves as the stress concentration leading to breakage is dependent on the positioning of the sample relative to the actuator, which in typical applications, will not change during the course of the experiment.

The force was applied normal to the axis of rotation. Hence the samples were chiefly loaded in shear. Compressive and oblique force vectors were not duplicated as such. Oblique loads may be disregarded as they resolve into a compressive and a shear component. Neglecting the compressive component may be justified inasmuch as a material's resistance to shear is half to one order of magnitude less than its resistance under compressive loads [36]. Hence the present experimental setup "assumes" that post and core build-ups essentially fail under shear rather than compressive load applications.

Nonetheless the testing setup could be enhanced by angulating the rotating collets in an upward direction thereby simulating and oblique occlusoapical force application.

Continuously altering this angle during the course of the experiment could further increase the field of force vectors applied.

4.2. *Analytical procedure*

Standard procedures in fatigue testing require that *S–N* diagrams (i.e. Wöhler curves) be drawn [37] (*S*: stress applied, *N*: number of cycles until failure). Such diagrams offer a full representation of a material's or component's fatigue resistance in the low-cycle (up to 10^4), limited endurance (10^4 to 10^7 cycles) and unlimited endurance (>10^7 cycles) ranges. Due to the large number of specimens required and the duration of the some of the runs (up to 10^7 to 10^8 cycles), drawing full *S–N* diagrams are heavy in their practical aspects.

An alternative approach consists in defining a cycle number (or range), which suitably characterizes the functional lifetime of a prosthetic component. In a previous report, we have extrapolated this number and set 10^6 cycles as approximately representing 1 year of clinical function [26]. The next step then consisted in identifying a procedural approach yielding a parameter that optimally describes a material's or component's fatigue resistance at 10^6 cycles. Several techniques are available to assess quantal (i.e. fail or not-fail) data [38]. The boundary technique rests on the premise that some combinations of load levels and cycle numbers are always conducive to failure while at others, the components will never fail [39]. In this technique, the probability of failure is assessed for a given number of cycles and two load levels. Both load levels must be located within the range of transition (i.e. they may either fail or survive the test). The load level at which 50% of the samples fail before reaching the maximum cycle number is then interpolated from both probabilities of failure.

Probit (probability bit) [40] analysis is usually recognized as yielding a high accuracy. Such tests, however, require in excess of 50 samples per datum and must be complemented with a hefty numerical treatment. By contrast, the staircase technique [30] as applied herein is a straightforward procedure, typically yielding valuable information after 15–20 runs only.

The drawback of the technique is exemplified in Fig. 4 in which F_{50}'s were calculated for the full data set and a set restricted to the last 10 runs. The issue as to which set optimally characterized F_{50} may be debated both ways: the full data set yields an optimal estimate of the mean's standard deviation while considering only the 10 last samples better characterizes the final F_{50} of the sample (as if the entry level had been set to F_{50} or if an infinite number of samples had been tested).

4.3. Fatigue resistance of the post-and-core structures

The results should be viewed in light of the above considerations regarding the mean (F_{50}) and its standard deviation. When considering the "10 sample" subset, 5 out of 7 post-cement combinations are statistical populations on their own. Conversely, when considering the full data set, the DT Lightpost and the Everstickpost form a group which distinguishes itself from the metal and ceramic posts, the Composipost and Easypost ranging somewhere in between. A broad reading of the results would allow the conclusion that the fatigue resistance of the two groups with the highest values (Everstickpost and DT Lightpost) is twice that of any of the metal or ceramic groups.

Interestingly post diameter was not a significant parameter in the equation that relates geometrical and material parameters to the observed fatigue resistance. Indeed, while it yield the strongest combination (i.e. highest F_{50}), the DT Lightpost was the one with the smallest diameter. Also, the present experiment provides no indication as to the contribution of adhesive cementation in the fibrous posts' F_{50}'s (relative to the metal and ceramic groups), complementary pull-out tests using the same combinations would be required. Definitive statements as to the contribution of friction versus bonding to internal dentin walls would be premature [41,42]. Nonetheless a recent publication reported superior bonding of Variolink relative to two competing products [43].

The present experiment would confirm a positive relationship between the decrease in the post's stiffness and an augmentation of the F_{50}'s observed. Due to inhomogeneous geometries, expressing stiffnesses in terms of GPa requires some approximations. Such attempts have been made yielding flexural modulus' of approximately 15 GPa for the Everstick post [44], 44 GPa for the DT Lightpost [45], 120–140 for the Composipost [45]. Dentin stiffness being charted in the 13–15 GPa range [46], the fibrous posts compare favorably with the elastic modulus' of stainless steel (215 GPa), titanium (120 GPa) and zirconia (200 GPa) [47].

Using the data generated in the present experiment, the fatigue resistance of post-and-core buildups may be related to similar data obtained for implant connectors. Such comparisons are possible since the experimental setups were identical (in particular with respect to the length of the lever). In previous studies, the F_{50}'s of solid conical implant abutments was in the 55N (ITI-Straumann) [29] to 72 N (replace select) [48] range. It follows that the fatigue resistance of natural teeth restored with post-and-core build-ups is two to seven times less than that of solid implant abutments.

Finally, when interpreting the data on failure modes, dentinal fractures occurred both in roots restored with posts of high- and lesser modulus of elasticity.

Acknowledgments

Our gratitude is expressed to Messrs P. Germann and C. Jaquet for machining the ancillary parts of the specimens. We are also grateful to Dr. Nacer Benbachir for testing part of the specimens.

REFERENCES

[1] Robbins JW. Restoration of the endodontically treated tooth. Dent Clin North Am 2002;46:367–84.
[2] Kwiatkowski S, Geller W. A preliminary consideration of the glass–ceramic dowel post and core. Int J Prosthodont 1989;2:51–5.
[3] Duret B, Reynaud M, Duret F. Un nouveau concept de reconstitution corono- radiculaire: Le composiposte. Chir Dent Fr 1990;60:131–41.
[4] King PA, Setchell DJ. An in vitro evaluation of a prototype CFRC prefabricated post developed for the restoration of pulpless teeth. J Oral Rehabil 1990;17:599–609.
[5] Bergman B, Lundquist P, Sjogren U, Sundquist G. Restorative and endodontic results after treatment with cast posts and cores. J Prosthet Dent 1989;61:10–5.
[6] Weine FS, Wax AH, Wenckus CS. Retrospective study of tapered, smooth post systems in place for 10 years or more. J Endod 1991;17:293–7.
[7] Morgano SM, Milot P. Clinical success of cast metal posts and cores. J Prosthet Dent 1993;70:11–6.
[8] Mentink AG, Meeuwissen R, Kayser AF, Mulder J. Survival rate and failure characteristics of the all metal post and core restoration. J Oral Rehabil 1993;20:455–61.
[9] Ellner S, Bergendal T, Bergman B. Four post-and-core combinations as abutments for fixed single crowns: a prospective up to 10-year study. Int J Prosthodont 2003;16:249–54.
[10] Creugers NH, Mentink AG, Fokkinga WA, Kreulen CM. 5-Year follow-up of a prospective clinical study on various types of core restorations. Int J Prosthodont 2005;18:34–9.
[11] Fredriksson M, Astback J, Pamenius M, Arvidson K. A retrospective study of 236 patients with teeth restored by carbon fiber-reinforced epoxy resin posts. J Prosthet Dent 1998;80:151–7.
[12] Glazer B. Restoration of endodontically treated teeth with carbon fibre posts-a prospective study. J Can Dent Assoc 2000;66:613–8.
[13] Ferrari M, Vichi A, Mannocci F, Mason PN. Retrospective study of the clinical performance of fiber posts. Am J Dent 2000;13:9B–13B.
[14] Paul SJ, Werder P. Clinical success of zirconium oxide posts with resin composite or glass–ceramic cores in endodontically treated teeth: a 4-year retrospective study. Int J Prosthodont 2004;17:524–8.
[15] Wiskott HW, Nicholls Jl, Belser UC. Stress fatigue: basic principles and prosthodontic implications. Int J Prosthodont 1995;8:105–16.
[16] Graf H, Geering AH. Rationale for clinical application of different occlusal philosophies. Oral Sci Rev 1977;10:1–10.
[17] van Eijden TM. Three-dimensional analyses of human bite-force magnitude and moment. Arch Oral Biol 1991;36:535–9.
[18] Wöhler A. Versuche zur Ermittlung der auf die Eisenbahnwagen-Achsen einwirkenden Kräfte und die Wiederstandsfähigkeit der Wagen-Achsen. English version in: Engineering (1867): Wöhler's experiments on the strength of metals 1860;10:583–616.
[19] Anderson RC. Inspection of metals. Metals Park, OH, ASM International, 1989.
[20] Libman WJ, Nicholls Jl. Load fatigue of teeth restored with cast posts and cores and complete crowns. Int J Prosthodont 1995;8:155–61.

[21] Basten CH, Nicholls Jl, Daly CH, Taggart R. Load fatigue performance of two implant-abutment combinations. Int J Oral Maxillofac Implants 1996;11:522–8.
[22] Wiskott HW, Belser UC, Scherrer SS. The effect of film thickness and surface texture on the resistance of cemented extracoronal restorations to lateral fatigue loading. Int J Prosthodont 1999;12:255–62.
[23] Wiskott HW, Doumas MT, Scherrer SS, Susz C, Belser UC. Microstructures of brazings and welds using grade 2 commercially pure titanium. Int J Prosthodont 2001;14: 40–7.
[24] Scherrer SS, Wskott AH, Coto-Hunziker V, Belser UC. Monotonic flexure and fatigue strength of composites for provisional and definitive restorations. J Prosthet Dent 2003;89:579–88.
[25] De Munck J, Braem M, Wevers M, Yoshida Y, Inoue S, Suzuki K, Lambrechts P, Van Meerbeek B. Micro-rotary fatigue of tooth-biomaterial interfaces. Biomaterials 2005;26:1145–53.
[26] Wiskott HW, Nicholls JL, Belser UC. Fatigue resistance of soldered joints: a methodological study. Dent Mater 1994;10:215–20.
[27] Wiskott HW, Nicholls JL, Belser UC. The relationship between abutment taper and resistance of cemented crowns to dynamic loading. Int J Prosthodont 1996;9:117–39.
[28] Coolidge E. The thickness of the human periodontal membrane. J Am Dent Assoc 1937;24:1260–5.
[29] Wiskott HW, Pavone AF, Scherrer SS, Renevey RR, Belser UC. Resistance of ITI implant connectors to multivectorial fatigue load application. Int J Prosthodont 2004;17: 672–9.
[30] Dixon WJ, Mood AM. A method for obtaining and analyzing sensitivity data. J Amer StatAssn 1948;43:109–26.
[31] Maennig W. Statistical planning of fatigue tests. Int J Fract 1975;11:123–9.
[32] Collins JA. Failure of materials in mechanical design; 1993. p. 369–74.
[33] Hsu YB, Nicholls JL, Phillips KM, Libman WJ. Effect of core bonding on fatigue failure of compromised teeth. Int J Prosthodont 2002;15:175–8.
[34] Goto Y, Nicholls JL, Phillips KM, Junge T. Fatigue resistance of endodontically treated teeth restored with three dowel-and-core systems. J Prosthet Dent 2005;93:45–50.
[35] Broek D. The practical use of fracture mechanics. Dordrecht, NL, Martinus Nijhoff, 2004.
[36] Craig RG, Powers JM. Restorarive Dental Materials. St. Louis, MO, Mosby, 2002.
[37] Klesnil M, Lukas P. Fatigue of metallic materials. Amsterdam: Elsevier Scientific Publishing Co.; 1992.
[38] Little RE, Jebe EH. Statistical design of fatigue experiments. London: Applied Science Publishers; 1975.
[39] Huysmans MC, van der Varst PG, Schafer R, Peters MC, Plasschaert AJ, Soltesz U. Fatigue behavior of direct post-and-core-restored premolars. J Dent Res 1992;71:1145–50.
[40] Finney DJ. Probit analysis: A statistical treatment of the sigmoid response curve; 1952. p. 236–45.
[41] Nuno N, Amabili M, Groppetti R, Rossi A. Static coefficient of friction between Ti–6Al–4V and PMMA for cemented hip and knee implants. J Biomed Mater Res 2002;59:191–200.
[42] Chai YS, Mai YW. New analysis on the fiber push-out problem with interface roughness and thermal residual stresses. J Mater Sci 2001;36:2095–1104.
[43] Goracci C, Sadek FT, Fabianelli A, Tay FR, Ferrari M. Evaluation of the adhesion of fiber posts to intraradicular dentin. Oper Dent 2005;30:627–35.
[44] Lassila LV, Tanner J, Le Bell AM, Narva K, Vallittu PK. Flexural properties of fiber reinforced root canal posts. Dent Mater 2004;20:29–36.
[45] Grenoble F. RTD, Mechanical properties. Recherches et Techniques Dentaires, 2006. http://www.rtd.fr.
[46] Sano H, Ciucchi B, Matthews WG, Pashley DH. Tensile properties of mineralized and demineralized human and bovine dentin. J Dent Res 1994;73:1205–11.
[47] Ashby MF, Jones DRH. Engineering materials, vol. 2: an introduction to microstructures, processing and design, 2nd ed. Oxford, E Butterworth-Heinemann, 1998.
[48] Wiskott HW, Jaquet R, Scherrer SS, Belser UC. Resistance of replace-select implant connectors under rotational fatigue loading. Int J Oral Maxillofac Impl, in press.

Please cite this article in press as: Wiskott HWA, et al., Rotational fatigue-resistance of seven post types anchored on natural teeth, Dental Mater (2007), doi:10.1016/j.dental.2006.12.001