Mechanical longevity estimation model for post-and-core restorations
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ABSTRACT

Objectives. The aim of this study was to integrate existing knowledge of in vitro strength of post-and-cores and masticatory loading to arrive at longevity estimates for post-and-core restorations when subjected to clinically relevant loads.

Methods. A biomechanical model was developed to predict the in vivo longevity. This method was applied to direct post-and-core restorations with amalgam or composite cores. Both experimental laboratory strength values and theoretical clinical strength values were used in the model. The restorations made in the laboratory were assumed to be of a higher quality than clinically made restorations, due to factors such as ease of manipulation, absence of saliva, etc. Both a high and low level of average masticatory loading were considered. The model was used to estimate the probability of mechanical failure before \(5 \times 10^6\) load cycles (5 to 15 years) for all combinations of load range and manufacturing quality.

Results. The calculated failure probability was effectively zero for most combinations except for a clinical quality core subjected to loads in the high range. There the probability of mechanical failure before \(5 \times 10^6\) cycles was estimated to be \(2 \times 10^{-5}\) for amalgam and \(5 \times 10^{-5}\) for composite cores. These results agree with the overall observed clinical failure rate of about 1% per year for post-and-core restorations.

Significance. The mechanical properties of the post-and-core restorations were adequate for clinically relevant loading conditions.

INTRODUCTION

Many factors govern clinical performance of post-and-core restorations, and they are only partly of a mechanical nature. However, reported clinical failures are predominantly mechanical: post dislodgment, post or crown fractures (Sorensen and Martinoff, 1984; Bergman et al., 1989; Turner et al., 1989; Morfis, 1990). Mechanical factors include both the internal mechanical properties of the build-up structure and the external mechanical demands made on it. Chewing and swallowing, and parafunctions such as clenching and bruxing, which are external demands, cause cyclic stress patterns in teeth and restorations. This is referred to as "cyclic loading". In combination with other factors such as thermal and chemical influences, cyclic mechanical loading causes a large proportion of the failures of all dental restorations.

Mechanical properties of dental materials and restorations are usually determined using quasi-static tests: tests where a load is applied and increased until failure occurs. However, the value of initial mechanical behavior for prediction of long-term clinical behavior is questionable. Cyclic loading causes material fatigue and the speed of the deterioration process may differ from material to material. In tests of 19 different brands of dental composites in three-point fatigue bending, Benkeser and Soltesz (1988) showed that the ranking of the composites for initial strength was different than for fatigue strength.

Determining the relationship between number of loading cycles and strength is a first step toward making better predictions and estimates of clinical longevity. However, mechanical performance does not depend on the properties of the materials alone. A restored tooth is a damaged structure. Every external influence on the structure, e.g., mechanical or thermal loading, increases the level of damage. The rate at which damage accumulates depends on shape, loading history and the damage already present.

Previous studies have reported the initial failure loads and fatigue behavior of standardized post-and-core restorations tested in vitro (Huysmans et al., 1992a; 1992b; 1992c). The aim of the present study was to arrive at longevity estimates for these post-and-core restorations when subjected to clinically relevant loads. A biomechanical approach was followed, aimed at integrating different engineering methods incorporating the experimental
results of the quasi-static and fatigue tests and of data about the masticatory loading (Van der Varst et al., 1991).

MATERIALS AND METHODS

Direct post-and-core restorations in extracted human upper premolar teeth were subjected to quasi-static and fatigue strength testing. Since the experiments were reported on previously (Huysmans et al., 1992a; 1992b), only a brief description of the experimental procedures is given here.

Decoronated upper premolar teeth were restored with a prefabricated titanium alloy post (Para Post Plus #4, Whaledent Int., New York, NY, USA) and an amalgam (Dispersalloy, Johnson & Johnson Dental Products Co., East Windsor, NJ, USA), or composite (Clearfil Core, Cavex Holland BV, Keur en Sneltjes MFG. Co., Haarlem, The Netherlands) core. In the quasi-static experiment, 61 teeth were subjected to a single load at 10, 45 or 90° to their long axis (9 - 12 teeth per loading direction and core material) until failure occurred. A schematic drawing of a restored tooth with the loading directions is shown in Fig. 1. For each restoration, the load at failure was recorded and the parameters of the Weibull distribution of the failure loads were estimated by Maximum Likelihood Estimation. In the fatigue experiment, 87 teeth were subjected to cyclic loading 5 to 21 d after restoration, at a frequency of 5 Hz, at an angle of 45° to the long axis of the specimens (10 - 15 teeth per load level and core material). The cycling load levels (that is, the load amplitudes) for amalgam specimens were 50, 60, 65 and 70%, and for composite specimens were 50, 60 and 70% of their mean quasi-static failure load. After 10^5 and 10^6 cycles, the specimens were checked for signs of failure, and returned to the testing set-up if still sound. After 10^6 cycles, the test was stopped and specimens again checked for failures. Failure probability at each of the experimental load levels after 10^5, 10^6 and 10^7 cycles was calculated from the formula:

\[ p_{\text{failure}} = \frac{r}{n+1} \times 100\% \quad (1) \]

where \( r \) is the number of failures and \( n \) is the number of specimens tested.

The laboratory data apply to a standardized restoration subjected to a known and standardized loading. The mechanical performance of these specimens is governed by a structure failure probability \( p \), a function depending on the dimensions of the specimens, the cycle frequency, the loading direction \( \phi \), the load level \( f \), and the number of cycles \( C \) (Van der Varst et al., 1991). For each material group, the data from the quasi-static experiments (case \( C = 1 \)) and the fatigue experiments (\( C > 1 \)) can be interpreted as experimental data about the dependence of the structure failure probability \( p \) on the load magnitude, load direction and number of cycles at a certain frequency.

The initial level of damage, shape factors, material properties and loading history determine the \( \text{in vivo} \) failure probability. Differences between the \( \text{in vivo} \) situation and the laboratory may exist for all these factors. Shape factors are largely neutralized because of standardized restoration dimensions, so a mean size may be assumed. \( \text{In vivo} \), the loading differs from the laboratory situation. First, the laboratory cycle frequency is not equal to the chewing frequency. Second, the \( \text{in vivo} \) loading direction is not fixed. Third, the load level, that is, the maximum of the load amplitude in a chewing cycle, is not constant. Fourth, \( \text{in vivo} \), the load levels must be considered as a stochastic quantity. This last fact is reflected by the large spread in the literature data about masticatory loading. Chewing frequency is about 1.25 to 2 Hz (Carlsson, 1974; Neil and Howell, 1988), whereas the laboratory cycle frequency was 5 Hz. This difference is known to have little influence on certain types of composites (Hähnel et al., 1986). For amalgam, no data on this subject exist. It is assumed that for amalgam, the influence of this difference is negligible. So, the relevant variables being load level \( f \), cycle number \( C \), and loading angle \( \phi \), the structure failure probability is a function of these variables: \( p = P(f,\phi,C) \). It is the probability that the longevity of a structure cyclically loaded at load level \( f \) and angle \( \phi \) is less than \( C \) cycles. Note that \( p \) is a conditional probability, the conditions being that the load level and loading direction have a known value.

Data from Graf (1975) suggest that when the load magnitude is at a maximum, the loading angle in a frontal plane is approximately 32.5° or 0.567 radians. Therefore, it suffices to take a fixed value \( \phi_o = 0.567 \) radians as the \( \text{in vivo} \) loading angle. The stochastic nature of the \( \text{in vivo} \) loading is accounted for by introducing a probability density \( D(\phi) \) for the load levels (Van der Varst et al., 1991). Combining the structure failure probability with the probabilistic description of the \( \text{in vivo} \) loading yields the \( \text{in vivo} \) longevity probability \( p_v \):
This is the probability that in vivo the longevity is less than \( C \) cycles.

The structure failure probability \( P(f, \phi, C) \). For all materials and three load angles, the quasi-static data are described rather well by a Weibull distribution (Huysmans et al., 1992b). So the Weibull distribution was also used for the fatigue case, with the Weibull parameters dependent on cycle number \( C \) and loading angle \( \phi \). Specifically:

\[
P(f, \phi, C) = \begin{cases} 
0 & \text{if } f < f_t(C, \phi) \\
1 - \exp \left( -\frac{f}{f_t(C, \phi)} \right)^{m(C, \phi)} & \text{if } f > f_t(C, \phi)
\end{cases}
\]

where \( f_t(C, \phi) \) is the threshold load, \( f_o(C, \phi) \) the reference load and \( m(C, \phi) \) the Weibull modulus (note that the quasi-static case is recovered if one takes \( C = 1 \)). Eq. 3 still holds too many unknowns to be solved with the available data. The problem is much simpler if the dependence of the failure probability on load level \( f \) and cycle number \( C \) is of the form \( p = P(A(C), \phi) \) in which \( A(C) \) is some function to be determined later. Expressing \( f \) as a function \( F \) of \( p, C, \) and \( \phi \); \( f = F(p, C, \phi) \), it can be shown that then the ratio \( F(p, C, \phi)/F(p, 1, \phi) \) should be independent of \( p \) (see Eq. 7), and this property can be used to experimentally check the assumption made above. For the Weibull distribution, this implies that:

\[
f_o(C, \phi) = A(C) \cdot G_o(\phi),
\]

and that the Weibull modulus is independent of \( C \), i.e., \( m = m(\phi) \). The mathematical proof of these assertions is omitted for reasons of space. The functions \( G_o(\phi) \) and \( G_t(\phi) \) represent the quasi-static values of the threshold and the reference load, respectively, because (without any loss of generality) \( A(1) = 1 \). For the structure failure probability, one then finds:

\[
P(f, \phi, C) = \begin{cases} 
0 & \text{if } f/A(C) < G_o(\phi) \\
1 - \exp \left( -\frac{f/A(C) - G_t(\phi)}{G_o(\phi)} \right)^{m(C, \phi)} & \text{if } f/A(C) > G_o(\phi)
\end{cases}
\]

Now all necessary functions can be determined. The Weibull parameter functions \( G_o(\phi) \), \( G_t(\phi) \) and \( m(\phi) \) were estimated from the quasi-static data. Because these experiments were performed at three different angles, interpolation to the value at the in vivo angle \( \phi_\text{iv} \) was possible. The fatigue experiments were performed at an angle of \( \phi = \pi/4 \). Solving Eq. 6 for \( f \) as function of \( p, C \) and \( \phi \), one finds next that:

\[
A(C) = F(p, C, \phi) / F(p, 1, \phi) = F(p, C, \pi/4) / F(p, 1, \pi/4).
\]

The fatigue experiments supply experimental data about \( F(p, C, \pi/4) \), for several combinations of \( F, C \) and \( p \), and the quasi-static experiments supply information on \( A(C) \).
Table 1 shows the results (mean, standard deviation, Weibull parameters) for the experimental groups of the quasi-static tests (Huysmans et al., 1992b). The results from the fatigue experiments combined with those of the quasi-static experiments are visualized in Figs. 3 and 4, each point representing an estimated failure probability based on the data (Huysmans et al., 1992c).

The structure failure probability and the in vivo lifetime probability are illustrated in Figs. 3 and 4 for both materials. The ratio's \( F(p,C,\pi/4)/F(p,1,\pi/4) \) are based on the experimental results. The assumption that this ratio is approximately independent of the failure probability \( p \) was judged to be true, and the function \( A(C) \) was found by least-squares curve fitting on the data. It was found that:

\[
A(C) = 1 - a \log C
\]

with \( a = 0.0774 \) for amalgam and \( a = 0.0815 \) for composite.

Graphs of \( A(C) \) as function of log \( C \) are also given in Figs. 3 and 4.

It was found that the dependence of \( m, G_v, \) and \( G_o \) upon the loading angle \( \phi \) could be described by:

\[
m(\phi) = b + d\phi + c\phi^2;
\]

\[
G_v(\phi) = g\phi^b;
\]

\[
G_o(\phi) = j\phi^k
\]

with constants \( b, d, e, g, h, j \) and \( k \) estimated by means of least-squares curve fitting (Table 2). The Weibull modulus \( m(\phi) \), the threshold \( G_v(\phi) \) and the reference \( G_o(\phi) \) were then determined for the in vivo angle \( \phi = \phi_v = 0.567 \) radians.

Table 3 contains these Weibull parameter sets for both the ideal case (case I) and the "clinical" quality case (case II).

For both materials, plots of the structure failure probability \( p \) are given in Fig. 5 for two fixed values of \( C \) (\( C = 10^5 \) and \( C = 10^6 \)). All curves apply to case I.

Finally, Fig. 6 shows the graphs of \( D_{\text{invo}}(\phi) \) for both materials (case II, \( \phi = \phi_v, C = 5 \times 10^6 \), an extrapolation of the experimental data with a factor 5). This product determines the in vivo longevity probability (see Eq. 2). The in vivo longevity probability for this combination of conditions after \( 5 \times 10^6 \) cycles was \( 2 \times 10^{-7} \) for amalgam and \( 5 \times 10^{-6} \) for composite. For both materials and considered cases, the in vivo probability of a longevity less than \( 5 \times 10^6 \) cycles was still zero if the loading was according to \( D_{\text{invo}}(\phi) \). The same result was found for case I combined with load level probability \( D_{\text{invo}}(\phi) \).
The use of probability distribution \( D(f) \) of the load levels implies a hypothesis about material behavior (Van der Varst et al., 1991). An important part of this hypothesis is that the growth of fatigue damage does not depend on the loading sequence (Paris-Giner-Miner law of damage growth). This hypothesis may not be true. For many materials used in aircraft engineering, the loading sequence does matter, and components are often tested using a simulation of the actual loading. Presently, the question of whether or not the growth of fatigue damage in composites or amalgam post-and-cores depends on the loading sequence cannot be settled because, to our knowledge, these materials have never been investigated from this point of view. Masticatory loading is extremely difficult to measure and highly dependent on food consistency, chewing habits and other scatter-increasing factors. The literature does not contain sufficient data for reconstruction of the actual loading conditions. The use of the probability function \( D(f) \) is, therefore, presently, the most simple way to account for the stochastic character of the masticatory loading.

For strength data, the threshold parameter of the Weibull distribution is known to be proportional to the inverse of the square root of the largest flaw sizes present in a material. Since all failures began in the core, the threshold parameter is proportional to the inverse of the square root of the largest flaw sizes present in the core, with the proportionality factor obviously dependent on the loading angle. If situations with equal loading angle are compared, the threshold parameter is a relative measure of the manufacturing quality of the cores, i.e. the larger the parameter, the higher the quality. The experimental specimens can be considered almost ideal, i.e., their cores having the smallest possible flaw size. Under clinical conditions, cores are expected to have much larger inherent flaw sizes. Assuming that in vivo, the inherent flaw size is four times that of laboratory specimens (De Groot, 1986), it follows that the in vivo value of the threshold is half the experimental value. The considered case II (Table 2) is therefore judged to be the more relevant case clinically.

During fatigue cycling, the damage which is initially present in a material gradually grows and decreases the load-bearing capacity of a structure. The structure behaves as if subjected to an ever-increasing effective load, and it is the effective load rather than the actual load that determines the failure probability. This phenomenon, one of the corner stones of modern continuum damage theories (Kachanov, 1986), is also reproduced by the failure probability \( p \) of Eq. 6. The quantity \( f/A(C) \) is the effective load since this variable determines the failure probability. Because \( A(C) \) decreases, the effective load increases as function of \( C \). For increasing values of \( C \), the structure failure probability \( p \) is, therefore, expected to shift to smaller values of the applied load levels \( f \). This behavior indeed occurs (Fig. 5).

The assumption that \( p \) depends through \( f/A(C) \) on load level \( f \) and cycle number \( C \), implies that \( P(p,C,f) \) should be independent of \( p \). Figs. 3 and 4 show experimental data about this. Ideally, all data points should lie on a straight line. Although this is not exactly the case, the deviations are small enough to consider the assumption valid to first order.

The in vivo longevity probability is determined by the product of load level probability density \( D(f) \) and the structure failure probability \( p(f,A(C)) \). Therefore, it is zero if these two functions do not overlap. For the load level probability density \( D_{\text{load}}(f) \), overlap was found for both materials and cases up to \( C = 5 \times 10^6 \) cycles. For cores having laboratory quality (case I), no overlap was found with \( D_{\text{load}}(f) \) either, meaning that the probability of a lifetime less than 5 million cycles is zero. The structure failure probability of cores having clinical quality (case II) did show overlap with the load level probability density \( D_{\text{load}}(f) \) after \( C = 5 \times 10^6 \) cycles (Fig. 7) leading to a small failure probability. Since the combination of clinical manufacturing quality (case II) with the load level probability density \( D_{\text{load}}(f) \) represents a worst case, and \( C = 5 \times 10^6 \) corresponds to a mechanical life of 5 to 15 years (Bates et al., 1976; Renggli et al., 1983), it was apparent, according to predictions of the biomechanical model, that the mechanical performance of the post-and-core restorations in vivo should be quite satisfactory for long periods of time.

The choice of loading angle was based on a single study (Graf, 1975). Perhaps future research will supply other data. This could modify the model, as strength so markedly depends on the direction of the load. Furthermore, in
each cycle, loads occur that are smaller than the cycle maximum but directed more unfavorably. These loads were not considered here, but they may have significant influence. Research into the functional loading of teeth, load magnitudes and loading directions is much needed to supply the necessary input for lifetime estimation models.

Most clinical studies have investigated cast post-and-cores. However, there is increasing evidence that the performance of prefabricated posts in conjunction with direct restorative materials is equal to or even better than that of the cast restorations (Sorensen and Martinoff, 1984). Within the confines of this study, those results were confirmed.

This research demonstrates a method for combining in a model laboratory data about strength and fatigue and data about masticatory loading to obtain estimates for the mechanical longevity of post-and-cores. Since the estimates that were obtained are of the same order of magnitude as observed clinically, the method can be used to rank new materials and designs on the basis of only laboratory data about strength and fatigue, combined with knowledge about masticatory loading. In this way, the method may contribute to increasing the efficiency of subsequent clinical tests.

In summary, the failure probability of direct post-and-core restorations as used in this study, due to physiological mechanical demands alone, is negligible. The mechanical properties of these restorations are adequate for clinically relevant loading conditions.

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