POLARIMETRIC OPTICAL FIBRE SENSING: MONITORING THE STRESS BUILD-UP IN DENTAL CEMENTS

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ABSTRACT

It is well known that during the curing of dental cements, polymerisation shrinkage induces unacceptable stress concentrations, which can result in cracks and an over-sensitivity of the teeth. We demonstrate that polarimetric optical fibre sensors can be used to quantitatively characterise this shrinkage. To determine the time evolution and the amount of this shrinkage we embed a highly birefringent optical fibre in the cement and analyse the change in optical polarisation at its output. This change is a measure for the dynamic stress-build up. In this paper we discuss the obtained experimental results and the repeatability of our characterisation method.

INTRODUCTION

Since several decades, dentists and their technical support teams have taken it as a challenge, not only to relieve tooth-aches, but also to control, imitate and even outperform nature. The beauty of a smile has become a driving force in the search for aesthetical tooth correction or replacement. In this context, new dental porcelains have attracted a growing attention since the early 1980ties [1]. The last progress in dental porcelains has reduced the drawbacks of the early materials. However, the role of the bonding resin cement remains a critical issue. For instance, when setting any composite resin cement between the properly prepared tooth surface and the porcelain facing, polymerisation is needed to transform the original monomer molecules to better-ordered and solid polymers [2]. The more molecules are converted to polymer chains to form rigid structures, the greater the volumetric shrinkage will be in the mass. When a cement polymerises without adhesion to others materials, this shrinkage process will not induce stresses in the cement. But in all-ceramic facings (tooth-cement-facing structure) adhesion is essential and inhomogeneous elasticity properties will induce stresses in all components of the structure. An all-ceramic facing is a precision fabricated full crystalline shell structure, bonded with a composite resin cement to a prepared tooth. The thickness of the facing ranges from 0.2 to 3 mm related to the configuration prepared by the dentist and the desired aesthetic result. In this paper we propose an original technique to characterise the amount of shrinkage of the cementing materials and the consecutive stresses appearing in the tooth-cement-facing structure during bonding. A simplified picture of this layered structure can be seen in Figure 1. Our polarimetric sensor is based on the use of highly birefringent single mode optical fibres. These fibres are fabricated to enhance their birefringence, which permits to maintain the particular polarization state of laserlight over long propagation lengths. The main drawback of these fibre sensors is that the effect of different external perturbations, such as temperature, strain, pressure and transversal force cannot

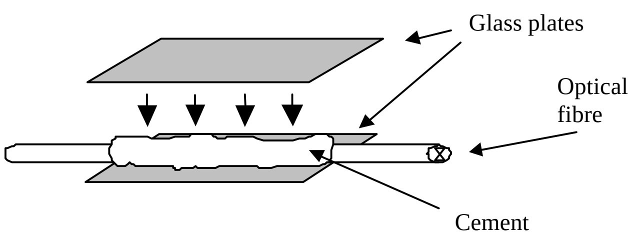


Figure 1: Three-layered configuration with the dental cement between 2 glass plates

be distinguished a priori. In this paper we present our experimental set-up, and show how the major axes of the HB fibre can be controlled with respect to the mechanical axes, in order to achieve reproducible results. We tested our set-up by characterising the shrinkage of a particular dental cement and show the reliability of these measurements. It should be pointed out that the biocompatibility of the materials involved in this polarimetric fibre sensor allows for real-time in-situ monitoring of the shrinkage of the dental cement, even in oral cavities.

THE POLARIMETRIC FIBRE SENSOR

All the fibres in our experimental set-up (Figure 2) are Fibercore HB800 bow-tie fibres. The light from a collimated laserdiode is coupled into the lead-in fibre and is polarised parallel to one of the optical major axes of the fibre. At the first connector, the linearly polarised light is split into two polarisation modes with an angle of $\pi/4$ with respect to the major axes of the lead-in fibre. The second connector couples the dephased field components into the lead-out fibre and the polarising beamsplitter cube, aligned to the major axes of the lead-out fibre. Here the collimated output light is split in its two perpendicularly polarised components and sent to the detectors [3].

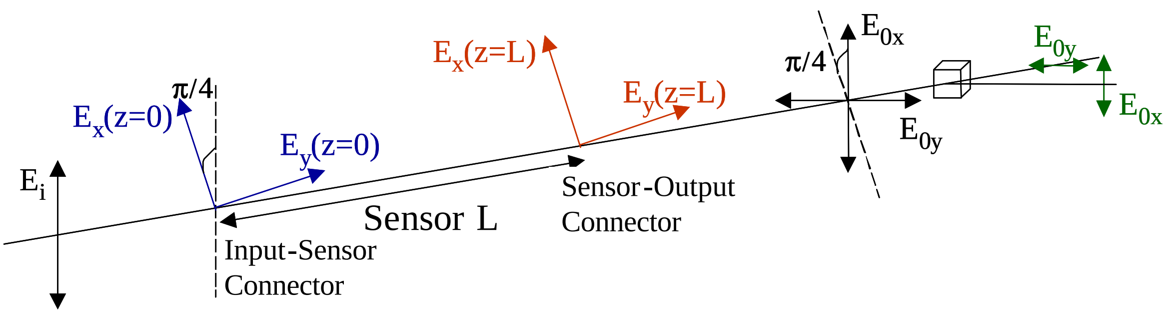


Figure 2: Polarimetric sensor configuration

As we are working towards stress measurements of curing dental cements, we start to measure the response of our sensor to hydrostatic pressure. To that end, we have inserted a part of the sensor fibre in an airtight plastic tube and manually increased the pressure to 10 bar via an air-pump from Druck Limited Co (Figure 3(a)).

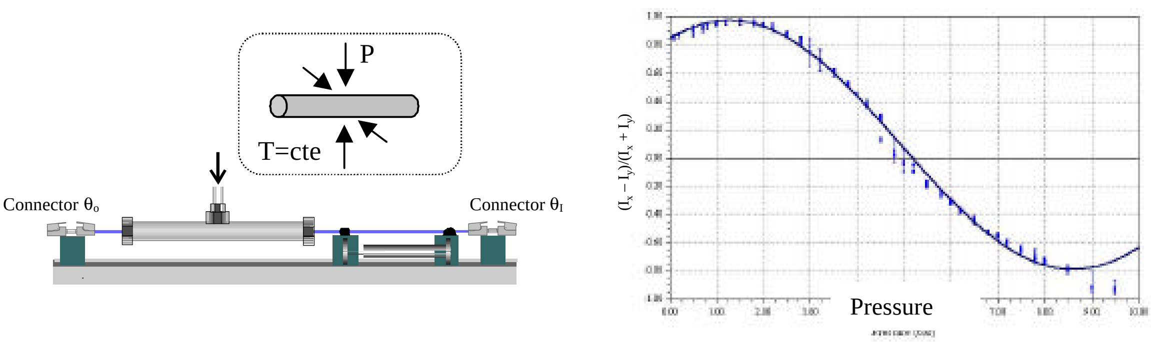


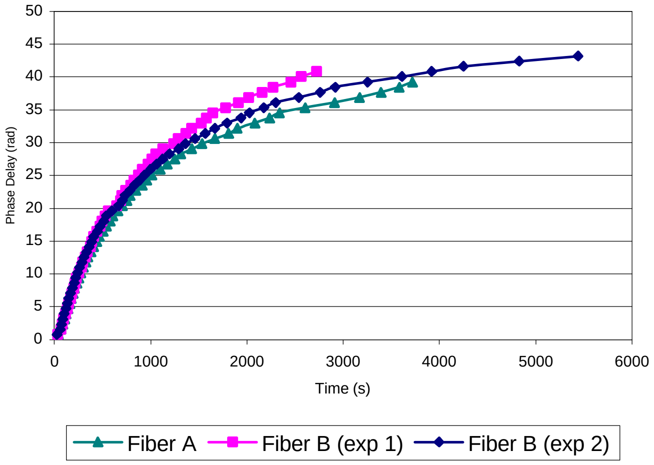
Figure 3: (a) Experimental set-up for measuring the pressure sensitivity; (b) Sensor response as a function of the pressure (HB800, L= 35 cm)

We measured the output polarisation state as a function of the pressure. In order to enhance the signal-to-noise ratio of our measurements, we have averaged 100 measurements for each value of the pressure. The measurements were controlled via a GPIB interface by Labview software. Figure 3(b) shows the sensor signal as a function of the pressure of the sensor fibre. Fitting of the experimental data with model equation $F(f, \frac{p}{4}, \frac{p}{4}) = h \cdot \cos\left(\Delta f_0 + \frac{\partial f}{\partial p} \cdot \Delta p \right)$ leads to a pressure sensitivity of $\frac{1}{L} \cdot \frac{\partial f}{\partial p} = (0.00915 \pm 0.00086) rad / (MPa \cdot mm)$.

We can conclude that our pressure sensitivity measurement corresponds to the pressure sensitivities found in literature [4,5]. Due to the anisotropy of the bow-tie fibre, an accurate control of the major axes of the fibre is necessary. When the optical axes of the fibre are aligned with respect to the mechanical axes of the system, one of the optical axes is in compression while the other is in tension, making the change of the birefringence and the sensor response the largest. When the major axes of the fibre are at π/4 with respect to the mechanical axes, the change in the birefringence becomes very small. This demonstrates the importance of the orientation of the fibre birefringence axes to the strain/stress mechanical axes [6]. Therefore it is crucial to control the orientation of the major axes of the polarization maintaining fibre before starting with the curing tests of the dental cements.

CHARACTERISATION OF DENTAL RESIN CEMENTS

We embedded the optical fibre sensor with maximum sensitivity in a layer of dental cement between two glass plates to simulate the "tooth-cement-facing" structure as shown in Figure 1. The experimental protocol consists of 3 phases: after calibrating and embedding the fibre in the cement, the resin is cured. The initiation of the curing process starts by exposing the restorative material to light with a wavelength in the order of 470 nm. We know that the measured phase, from the moment the curing starts, is proportional to the induced stress anisotropy in the core of the fibre and that this stress anisotropy is proportional to the shrinkage of the cement [7]. This means that the measured phase shift as a function of the time is proportional to the evolution of the shrinkage with time.



	a (rad)	τ (s)
Fibre A	38.16	935
Fibre B (exp 1)	42.27	1010
Fibre B (exp 2)	40.77	952

Figure 4: (a) Measured phase shift as a function of the time; (b) Exponential fit on the measured data with a the magnitude of the shrinkage and the time constant τ

In Figure 4(a) we have plotted the measured phase shift at the start of the curing of a dental resin cement. To investigate the reproducibility of the results we have done the same experiment twice on another fibre using the same type of resin. The shrinkage response can then be given in approximation by the Kohlrausch-Williams-Watts exponential growth curve [8]: $Phase\ shift = a\left(1 - e^{\left(-\frac{t}{\tau}\right)}\right)$ with a the magnitude of the shrinkage after an infinite time and τ the characteristic time constant for the shrinkage as depicted in Figure 4(b). The characteristic time constant τ gives us the time when the shrinkage reaches $(1-e^{-1})$ or 63.2% of its saturation value a. From this table we can conclude that the deviation of a measurement with another fibre has the same magnitude as with the same fibre. The standard deviation can be improved if we can accurately control the orientation of the major axes and hence the amplitude of the sensor signal. The cement used in the previous experiment induces an average stress of 88.3±9.48 MPa for the configuration shown in Figure 1, while the average time constant reaches a value of 965.7±39.3 s. In the future we will use this to compare the shrinkage behavior of different dental cements.

CONCLUSION

In this paper we have demonstrated a new method to characterise dental resin cements using polarimetric optical fibre sensors. We have measured the sensitivity of the polarimetric sensor for the external pressure. Using the three-layered structure tooth-cement-facing we have seen that the measured response of the sensor was a function of the rotation of the major axes of the fibre. Therefore we first optimised the control on the orientation of these principal optical axes. Afterwards we characterised a dental cement using the calibrated fibre sensor and we demonstrated the repeatability of our characterisation method. As a conclusion we can say that this polarimetric sensor has two applications: dentists can use it to monitor the hardening of the cement during in-vivo measurements and can therefore also control the stress in a facing based restoration. Secondly the sensor can be used to perform quality control on batch produced dental cements. Because of the complexity and the high degree of production turn-over in the commercial development of dental composite resin cements (an average of 1 type every 2 years), there seems to be a real need to optimise the cement and preparation method for each configuration. Although we reported on the curing of dental cements only, this technology holds potentialities for all applications where only a small amount of material is available for analysis. At the conference we will highlight the latest polarimetric responses of different dental resins obtained with a currently developed motorised set-up.

REFERENCES & ACKNOWLEDGMENTS

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