Optical fibre Bragg grating sensor based mode shape identification using sub-microstrain amplitude excitation

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Abstract

Vibration-based damage identification is a non-destructive method that enables health monitoring of civil engineering structures. It aims to detect the presence and growth of damage by following up on sudden or gradual changes of natural frequencies, damping factors or modal displacements of a structure under test. Damage identification based on the modal characteristics of structures is known to suffer from the low sensitivity of these natural frequencies and modal displacements to certain types of damage. Modal strains and curvatures, however, can be more sensitive to local damage. Directly monitoring these quantities in a quasi-distributed manner is either cumbersome or requires substantial investments with current measurement techniques due to the very small strain levels in the sub-microstrain range (~1µε) that result from ambient or operational excitation. Here we show that such measurements can be successfully carried out with a wavelength-multiplexed array of fiber Bragg grating (FBG) based sensors mounted on an inexpensive custom transducer. We report on labscale dynamic tests with free-free boundary conditions on a 1.7 m reinforced concrete beam with a cross section of 125x225 mm$^2$, equipped with quasi-distributed FBG sensors. We compare the response of 14 bare FBG-based sensors mounted to the side of the concrete beam with 14 FBG-based sensors that were pre-installed on a dedicated strain amplifying transducer for equivalent gauge lengths. The concrete beam was excited with an impact hammer at low excitation levels, yielding strain values close to those experienced by bridges under ambient excitation. The wavelength shifts of both sets of FBG-based sensors were acquired by an entry-level commercially available grating interrogator, and the corresponding strain data was post-processed with the aim to identify the strain mode shapes of the concrete beam. Our results show that the FBGs mounted on our transducers are able to identify the first bending mode (~300 Hz) at those relevant excitation levels owing to their strain resolution that is 23 times better than that of the bare FBG-based sensors. We anticipate this demonstration to be a starting point for the practical implementation of relatively low-cost strainmode-shape based structural health monitoring of civil concrete structures such as bridges.
1. Introduction

Structural Health Monitoring (SHM) methods typically serve either local or global damage identification strategies. Global methods can only determine whether damage is present or not in the entire structure without locating said damage, while local methods provide an indication of where damage occurred without the possibility to monitor the entire structure at once. In this respect relying on vibration-based damage identification provides an interesting alternative as this potentially allows for detecting and locating the occurrence of damage in an entire structure.

The fundamental idea for vibration-based damage identification is that the damage which occurred in a structure can modify its physical properties (mass, damping and stiffness) and thereby cause changes in its modal properties (natural frequency, modal damping and mode shapes). The modal parameters of a structure can be obtained by carrying out a forced or ambient vibration test on a structure using system identification methods. By comparing these measured modal parameters with the modal parameters of a numerical model of the same undamaged structure, detection and localization of a damage is possible. There are three main damage identification methods: natural frequency-based method, displacement mode shape-based methods and curvature/strain mode shape-based method [1]. However, in the two first methods, changes in the environmental conditions lead to varying eigenfrequencies and mode shapes, which can completely mask the presence of damage [2]. These methods also suffer from low sensitivity of the eigenfrequencies to certain types of damage, especially to local damage of moderate severity [3]. On the other hand, modal characteristics obtained from dynamic strain measurements (modal strain or modal curvatures) are more sensitive to local damage [4], [5].

Nowadays, the biggest challenge of Vibration-Based Structural Health Monitoring (VBSHM) is to develop a monitoring system that is sensitive to local damage, that can be easily mounted on extended structures and that is cost-effective. Monitoring is typically done on the basis of strain measurements and the latter conventionally rely on the use of strain gauges. These devices are well-known and widely commercially available. However, strain gauges are also known to feature a limited strain sensitivity (∼1µε), to suffer from drift, to be sensitive to moisture and electromagnetic interference (EMI). Optical fiber sensors, and more particularly FBG-based sensors, outperform traditional sensor technologies, as they are lightweight, small in size and offer easy installation, resistance in harsh environment and convenient multiplexing capabilities [6]. In the past years, FBG sensors have been used e.g. for real-time monitoring of railway infrastructure [7], for monitoring of bridge structures, such as the Tilff Bridge in Belgium [8], the Tsing Ma Bridge in Hong Kong [9], Horsetail Falls Bridge in the United States [10] or the Sesia Viaduct in Italy [11], but these methods require using artificial high-amplitude excitations. Our objective is to exploit ambient excitation, leading to modal strain amplitudes in bridges that are typically lower than 1µε [9]. Detecting such small strains with FBGs requires a Bragg wavelength detection resolution that is outside the capabilities of most entry-level FBG interrogators.

The aim of the study is therefore to enable the measurement of dynamic strain serving vibration-based SHM, with a resolution that is on the order of 0.1µε or better. To do so a mechanical strain amplifying transducer equipped with FBG sensors [12] was
compared with that of FBGs directly clamped to the structure array to extract the modal parameters of a reinforced concrete beam under very low excitation levels. The rest of this paper is structured as follows. In section 2, the strain amplifying transducer is introduced and the strain sensitivity of the transducer measured experimentally and numerically using a finite element (FE) method is presented. Section 3 then details the experimental setup for dynamic testing and section 4 summarizes the experimental results of this dynamic testing on a reinforced concrete beam. Section 5 closes our paper with a summary and conclusions.

2. A mechanical strain amplifying transducer

To enable the identification of strain mode shapes under the presence of sub-microstrains strain levels, a strain sensor has been developed, which combines a FBG sensor with a dedicated mechanical transducer that mechanically amplifies the strain applied to the transducer itself.

In this paper, the size of the transducer was adapted, to enable measurements on a 1.7 m long concrete beam. The transducer measures 94 mm by 54 mm, with an effective gauge length of 80 mm. The first eigenfrequency of this transducer is 1103 Hz, as obtained from simulations, which is well above the first resonance frequencies of a 1.7 m long concrete beam (303 Hz). 14 transducers were manufactured according to the design shown in Figure 1. The FBG sensors mounted on these transducers are commercially available ORMOCER® coated draw tower gratings (DTG®) [13]. A first grating (DTG1) was installed near the fixation points to provide a reference measurement of the total strain applied to the transducer and a second grating (DTG2) in the region with amplified strain. The complete manufacturing and preparation of the transducers has been reported earlier [14].

A three-dimensional (3D) FE model of the transducer was built in COMSOL®[15]. The model takes into account the material of the transducer, the glass optical fiber and the adhesive applied to fix the fiber in the V-grooves. The strain amplification calculated from simulations equals 24.2. The average strain amplification for the 14 transducers was measured to be $23 \pm 0.4$, which agrees well with the FE modelling.

Figure 1. Photograph of the fabricated transducer with indication of the location of the FBGs and the glued fiber sections.
3. Experimental setup

As test structure, a reinforced concrete (RC) beam is considered (Figure 2). The beam had length of 170 cm with a cross section of 125x225 mm$^2$. It was suspended at both ends with flexible springs to approximate free-free boundary conditions.

![Figure 2. The reinforced concrete beam showing the installed array of 14 strain transducers.](image)

One chain of FBGs on mechanical strain amplifying transducers was attached at one side of the beam (see Figure 2) along its longitudinal direction, to measure the axial dynamic strains in the x-direction (see also Figure 5). To mount the transducers on the RC beam a washers were glued at the fixation points to the back of the transducers (Figure 3) and then adhesive was applied [16] to the washers to fix the transducers to the RC beam. The center-to-center distance between two consecutive transducers was around 10 cm.

![Figure 3. Washers glued at mounting locations on the transducer.](image)
One chain of 14 regular FBG clamped strain sensors was attached to the opposite side of the beam. The distance between two subsequent sensors was also around 10 cm. The FBG strain sensors were mounted with a clamping system (Figure 4), instead of being directly mounted on the concrete surface [17]. This method allows measuring the average strain between the fixation points and straightforwardly removing the fiber after the experiment.

![Figure 4. Fiber clamping system with glued support blocks for installing an array of regular FBG sensors with a gauge length of ca. 10cm.](image)

**4. Dynamic tests on the concrete beam**

For the dynamic tests, the beam was repeatedly impacted with a hammer from the top at one of its corners for a total duration of about 30 seconds (Figure 5). Two dynamic tests were performed with an average force of ~300 N and ~5.4 kN. The FBG sensors were interrogated at 1 kHz with a commercially available spectrometer-based acquisition system (FBG-scan 704D) that featured a Bragg wavelength detection resolution of 1 pm [18].
Figure 5. Schematic of the experimental setup of the dynamic test on the reinforced concrete beam.

Figure 6 (a) shows the strain obtained with a selected FBG mounted on a transducer during the first dynamic test (other FBG sensors return similar results). As expected the strain measured by this FBG (~20 με) is significantly larger than that recorded by the clamped FBG (~1 με) at the opposite side of the beam (Figure 6 (b)). The ratio of both strain levels is in reasonable agreement with the finite element modelling and calibration of the transducers. Because the wavelength resolution of the FBG interrogator is 1 pm and the sensitivity of the FBG sensors is 1.2 pm/με, the minimum strain measured by FBG sensors is only 0.8 με (see Figure 6 (b)). Figure 7 shows the results for the second dynamic test, which yields the same strain ratio: the maximum strain measured by the FBG on the transducer was ~60 με, whilst that obtained from the clamped FBG sensor was ~3 με.
Figure 6. Strain measurements during dynamic tests with a force of 300 N recorded with an FBG mounted on a transducer (a) and an FBG directly clamped to the beam (b).

Figure 7. Strain measurements during dynamic tests with a force of 5.4 kN recorded with an FBG mounted on a transducer(a) and an FBG directly clamped to the beam(b).
To extract the modal characteristics from the measurements shown above, we applied the so-called covariance-driven Stochastic Subspace Identification (SSI-cov), which is an output-only identification technique [19]. The SSI-cov algorithm also provides the 95% confidence interval ($\sigma$) for quantifying the uncertainty of the identified modal characteristics. MACEC was used, which is a Matlab toolbox for experimental and operational modal analysis [20], to carry out this time-domain system identification.

Figure 8 shows the mode shapes of the first bending mode of the beam obtained from SSI-cov. To identify strain mode shapes, average of two consecutive sensors was taken. The strain mode shape cannot be identified using measurements from the clamped FBG strain sensors with an excitation force of 300 N, due to the low strain levels.

Figure 8 (a) shows the strain mode shape of the first bending mode for both dynamic tests at 300 N and 5.4 kN obtained by the FBGs mounted on the transducers. The mode shapes are very similar for both tests. The maximum difference between both tests is 0.03, which indicates the repeatability of the results. The mode shape does not fit perfectly with the anticipated arch-like first bending mode. This deviation most likely results from a variation in the strain amplification value between the different strain transducers, which in its turn stems from variations in the installation of the transducers. This is nevertheless the first demonstration of strain mode identification based on an array of FBGs on a strain enhancing transducer. Figure 8 (b) compares the first bending mode obtained with the two types of sensors during the 5.4 kN excitation. At this load level, also the clamped FBG sensors allow extracting the strain mode shapes.

![Figure 8](image_url)

*Figure 8. The modal strain shape of first bending mode (B1) measured with FBGs mounted on strain transducers for both dynamic tests (a) and measured with both the clamped FBGs and FBGs on the strain transducers for the dynamic test with an average force 5.4 kN (b).*
5. Conclusions

Vibration-based structural health monitoring of civil concrete structures requires measuring dynamic strain with a resolution of the order of 0.1με. For this purpose, a lab-scale reinforced concrete beam was equipped with an array of 14 wavelength multiplexed FBGs that were pre-installed on strain amplifying transducers. The average experimentally derived strain amplification over the fourteen transducers is 23 with a standard deviation 0.4, which agrees well with the finite element modelling (24.2). This indicates that such transducers can be fabricated in a repeatable manner. Two dynamic tests were performed with an average force 300 N and 5.4 kN. The results obtained with the strain amplifying transducers and those obtained from an equal amount of FBG sensors directly attached to the concrete beam were compared. The first bending mode of the concrete beam can only be identified from data measured by the strain amplifying transducers. These results support that dedicated strain amplifying transducers can be potentially applied for vibration-based structural health monitoring of civil concrete structures under ambient or operational excitation.

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