Identification of modal strains of a pre-stressed concrete beam during progressive damage testing

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Keywords: Condition monitoring, optical fiber sensor, dynamic strain sensing, progressive damage testing, system identification

Abstract

Vibration-based Structural Health Monitoring (SHM) of civil structures currently suffers from a low sensitivity of natural frequencies and modal displacements to certain types of damage while the sensitivity to environmental influences may be sufficiently high to completely mask the effect of severe damage. Modal strains and curvatures are more sensitive to local damage, but the direct monitoring of these quantities is challenging due to the very small strain levels occurring during ambient, or operational excitation. In the present work, a pre-stressed, concrete I-shaped beam was subjected to a four-point, static bending test. The beam was subjected to six loading cycles of increasing load, before failing at the last cycle. Dynamic measurements were conducted on the beam at the beginning of each cycle and hammer impacts were used as dynamic excitation. The response of the beam to the applied force was recorded with accelerometers and two chains of multiplexed Fiber-optic Bragg Grating (FBG) strain sensors attached through a novel external clamping system at the top and the bottom flange, such that macro-strains were measured. Subsequently, the identification of the modal characteristics (eigenfrequencies, mode shapes and modal strains) was conducted with subspace identification. In order to achieve accurate identification of the modal strains, a novel optical signal processing technique that enables to obtain sub-microstrain accuracy with FBG strain sensors was implemented. The evolution of the modal characteristics of the beam, after each loading cycle is investigated. Changes of the eigenfrequencies, of the mode shapes and modal strains were observed, indicating the presence of damage.

1. INTRODUCTION

Vibration-Based Structural Health Monitoring (VBSHM), can be a successful approach for damage identification and structural condition assessment of civil structures, e.g. bridges, dams and tunnels [1]. A drawback of the method is that currently it suffers from low sensitivity of the eigenfrequencies to certain types of damage, especially to local damage of moderate severity [2]. Moreover, the influence of the environmental factors (e.g. temperature) on eigenfrequencies and mode shapes can be high enough to completely mask the presence of damage [3]. In contrast, modal characteristics obtained from dynamic strain measurements, such as modal strains and modal curvatures, are much more sensitive to local damage [4]. The introduction of fiber-optic sensing systems, that can accurately measure dynamic strains while also offering ease of installation, resistance in harsh environment and long-term stability, contributed to an increased interest in adopting these systems for VBSHM applications [5]. In this context, the present work explores the ability to identify the modal characteristics of a pre-stressed
concrete beam and consequently the damage that is induced in it through a progressive damage test, with the implementation of standard Fiber-optic Bragg Grating (FBG) strain sensors.

The FBG strain sensors have been successfully used for monitoring civil structures but mainly for measuring of static loads while the amount of sensors used was limited. The current challenge for the VBSHM of civil structures is to find monitoring systems that are easily implemented over large areas, are sensitive to local damage, while are also able to measure very small strain values and are cost-effective [6]. The FBG strain sensors can provide a good trade-off solution to these requirements. In this context, the aim of this study is to directly measure in dense grid the very small dynamic strains that occur in civil structures, such as bridges, during operational or ambient excitation and to identify the system characteristics from this data. By tracking the shifts in the values of the characteristics, the identification of potential damage is possible.

Two chains of multiplexed FBG strain sensors were used to measure the response of the beam to the input force. In addition to the FBG strain sensors, conventional accelerometers were also used. The beam was excited with hammer impacts imposed at one of its ends. The dynamic tests were conducted at the beginning of each loading cycle, were the applied load was equal to zero. Data from both types of sensor were used for system identification and consequently for modal analysis and dynamic characteristics identification. The obtained dynamic characteristics from both analyses were compared to cross-validate the two methods. A novel external clamping system that allows to reuse the FBG fibers, since they are not directly glued on the beam, was also introduced in this experiment.

2. EXPERIMENTAL SETUP

As test structure, a pre-stressed concrete beam is considered (Figure 1). The beam has a length of 7.0m and a height of 0.63m with an I-shaped cross section (Figure 2). It is seated on a steel supporting table through two supports at 1.0m from the ends (Figure 3). The boundary conditions approximate these of a simply supported beam, although an interaction between the beam and the steel table is expected as the steel table supports can not be considered as infinitely stiff with respect to the concrete beam. The beam was subjected to dynamic tests after unloading during a progressive damage test.

2.1 Progressive damage test

During the progressive damage, 4-point static bending test (Figure 4), the beam was subjected to 6 loading cycles of increasing load. The beam was designed to fail in shear at the end of the last loading cycle. During loading, the force was applied to the beam at two points located 0.3m respectively to the middle of the beam, as shown in Figure 4. The maximum applied force at each cycle is summarized in Table 1 while the quasi-static loading history is illustrated in Figure 5.
Figure 4: Experimental setup of the 4-point static bending test

Figure 5: Quasi-static loading history of the beam. Tests 1a-1b with black, 2a-2b with red, 3a-3b with magenta, 4a-4b with blue, 5a-5b with green and 6a-6b with orange.

Table 1: Maximum quasi-static force per loading cycle and dynamic tests numbering

<table>
<thead>
<tr>
<th>Loading Cycle</th>
<th>Conducted Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st (116KN)</td>
<td>1a, 1b</td>
</tr>
<tr>
<td>2nd (233KN)</td>
<td>2a, 2b</td>
</tr>
<tr>
<td>3rd (256KN)</td>
<td>3a, 3b</td>
</tr>
<tr>
<td>4th (282KN)</td>
<td>4a, 4b</td>
</tr>
<tr>
<td>5th (310KN)</td>
<td>5a, 5b</td>
</tr>
<tr>
<td>6th (405KN)</td>
<td>6a, 6b</td>
</tr>
</tbody>
</table>

2.2 Dynamic Tests

At the beginning of each cycle, when the applied force was equal to zero and the press-head of the bending machine detached (Figure 4), 2 dynamic tests were conducted; therefore data from 12 tests are available. The numbering of the conducted tests is summarized in Table 1. The same number is assigned to the tests of the same loading cycle while the individual tests of each cycle are noted with a or b. The time instances that the tests were conducted are shown in Figure 5. Two kinds of sensor were used to record the response of the beam to the input force: accelerometers and Fiber-optic Bragg Grating (FBG) strain sensors. Hammer impacts were used for the dynamic excitation of the beam. The location and the direction that the excitation was applied coincides approximately with the accelerometer in location 1 (Figure 6).

2.3 Accelerometers

Uniaxial accelerometers were fixed at 14 locations on the edges of the top flange of the beam, to measure the vertical accelerations (z-direction) as shown in Figure 6. The distances between two consecutive accelerometers is 50cm. A National Instruments (NI) acquisition system was used for the recording of the accelerations. The sampling frequency was set to $f_s=1651$ Hz.
2.4 Strain Sensors

Two chains of multiplexed FBG strain sensors were attached at one side of the upper and lower flanges of the beam along its longitudinal direction, to measure the axial dynamic strains in x-direction, as shown in Figure 7. Both fibers contained 14 FBGs. The distance between two consecutive sensors is 50 cm. In total, 15 supports were used for each fiber while one sensor exists in between two supports, measuring the average strain or macro-strain. An important advantage of measuring macro-strains is that it is easier to identify the cracks that are induced to the beam since a relative measuring distance of 50 cm increases the identification capability. Only when strains are measured over a long enough distance, typically bridging two cracks, the Bernoulli’s assumptions are fulfilled. On the contrary, when a sensor is directly glued on the beam and local strains are measured, the identification of cracks is much harder, as strains are very dependent on their position with regard to the cracks.

The fibers were attached to the beam through a novel clamping system, instead of directly glued to it, since the roughness of the concrete surface would not allow an adequate strain transferring and the obtained measurements would not be accurate. Moreover, the fibers can be reused in this way. The fibers were pre-stressed with an average value of $1.900 \mu \varepsilon$ at the top and $240 \mu \varepsilon$ at the bottom. The pre-stressing of the top fiber was selected to be high enough to ensure that it would remain in tension taking into account that the top flange is under compression due to the applied force.

The clamping system is shown in Figures 8 and 9. The support consists of two parts, the base and the cap. The fiber is fixed between the two parts, by firmly screwing the cap to the base, so that it can not slide and the strains are adequately transferred from the beam to the sensors. Rubber is used in the connection to secure that the fiber will not get damaged. A FBGS FBG-SCAN 700 acquisition system was used for measuring the dynamic strains. The sampling frequency was selected to be $f_s = 1651$ Hz. It is important to note here, that both fibers were covered with thermal insulation during the tests to ensure that temperature fluctuations in the laboratory would not affect the measurements (Figure 2).
2.5 Peak-shift Algorithm

The ability to determine the Bragg wavelength shift with adequate accuracy and precision is essential. When the measured strains create wavelength shifts lower than the resolution of the acquisition system, the implementation of a peak-shift algorithm that will interpolate sub-resolution down to the desired level is mandatory. In the described experiment, the Fast Phase Correlation (FPC) [7, 8] algorithm was used to increase the spectral resolution of the FBGS interrogator from 90pm (hardware resolution) to 1pm or 0.8µε, since the measured strains were of this magnitude. The average measured Root Mean Square (RMS) strain values of the sensors in the middle of the beam where about 0.5µε for dynamic loads with RMS force values of 100N.

3. SYSTEM IDENTIFICATION

The system identification was conducted with MACEC, a MatLab toolbox for experimental and operational modal analysis [9]. Two identification techniques were applied, the covariance-driven Stochastic Subspace Identification (SSI-cov), which is an output only identification technique [10] that allows also the uncertainty quantification of the identification [11], and the Combined deterministic-stochastic Subspace Identification (CSI) [12] where both the input force and the output measured data (accelerations, strains, etc.) are used for the identification.

4. ACCELEROMETER DATA MODAL ANALYSIS

The first three bending modes about the major axis of the beam were identified. Modes were selected from stabilization diagrams and have a minimum Model Phase Collinearity (MPC) value of 0.95. The MPC is an indicator that checks the degree of complexity of a mode and values close to unit translate into almost purely real modes [13]. The evolution of the eigenfrequency values is shown in Figure 10. For bending modes 2 and 3, a clear reduction of the average eigenfrequency values in each loading cycle can be observed. We can conclude that the eigenfrequencies of the beam for the undamaged and the damaged condition, after averaging their values for the tests of the first (1a-1b) and last (6a-6b) loading cycle, are approximately:

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>1\textsuperscript{st} Mode [Hz]</th>
<th>2\textsuperscript{nd} Mode [Hz]</th>
<th>3\textsuperscript{rd} Mode [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSI-cov (undamaged)</td>
<td>72.31±0.04</td>
<td>173.00±0.07</td>
<td>317.84±0.30</td>
</tr>
<tr>
<td>CSI (undamaged)</td>
<td>72.33</td>
<td>172.98</td>
<td>317.98</td>
</tr>
<tr>
<td>SSI-cov (damaged)</td>
<td>72.55±0.15</td>
<td>170.19±0.17</td>
<td>308.49±0.43</td>
</tr>
<tr>
<td>CSI (damaged)</td>
<td>72.68</td>
<td>169.90</td>
<td>308.64</td>
</tr>
</tbody>
</table>

Table 2: Average eigenfrequencies of tests 1a and 1b (1\textsuperscript{st} Cycle - 116KN) - undamaged condition and of tests 6a and 6b (6\textsuperscript{th} Cycle - 405KN) - damaged condition. The 95% confidence interval for the SSI-cov is also presented.

The percentile reduction of the eigenfrequency values is about 2% for the second and 3% for the third bending mode when compared to the undamaged condition. The continuous reduction of the eigenfrequency values, for modes 2 and 3, indicates a reduction of the beam’s stiffness and consequently damage which is in agreement with the observations on the beam, where the shear cracks were increasing by each loading cycle in number, width and length. On the contrary, the damage was not identified by the first mode due to the pattern of the damage. The beam was designed to fail in shear, between the supports and the location of the quasi-static force (Figure 4). At these zones, the curvatures of the first bending mode, as it is shown in Figure 11a, are almost zero and as a result the reduction of the stiffness does not influence the mode shape and the eigenfrequency. The eigenfrequency identification can be considered as successful since the 95% confidence interval, as obtained from the SSI-cov identification [10, 11], is relatively narrow and the differences between SSI-cov and CSI are small.
Combined graphs with all the identified mode shapes of the six loading cycles are shown in Figure 11 to demonstrate their evolution during the experiment due to the imposed damage. The presented mode shapes were obtained from the CSI identification. A least-squares fit was applied for the determination of the scale factor $c$ that links the mass normalized mode shapes of the various tests with the mass normalized mode shapes of test 1a. The first two bending modes do not pose significant amplitude or shape changes and as a result the damage is not identified. On the contrary, the third bending mode shape poses significant amplitude and curvature changes at the areas of damage (500–2500mm and 4500–6500mm) for the tests of the last loading cycle which is a clear indication of the presence of damage. In Figure 11, the two distorted mode shapes are corresponding to tests 6a and 6b of the sixth loading cycle. The interaction of the beam with its steel supporting table is apparent in Figures 11a and 11c, where the modal displacement of the supports is significant.

5. FIBER-OPTIC BRAGG GRATINGS (FBG) STRAIN DATA MODAL ANALYSIS

The system identification was conducted with the SSI-cov algorithm. The CSI technique was not applied here since the input force cannot be measured with the FBGS acquisition system. Furthermore, since the strain acquisition system had only one input channel, the simultaneous measurement of two fibers was not possible. Thus, the tests that are noted with $a$ correspond to the top flange fiber and with $b$ to the bottom fiber (Table 1).

The first three bending modes of the beam were identified from both top and bottom flange fiber dynamic strain data. All modes were selected from stabilization diagrams with MPC values higher than 0.95 except for the third bending mode of the bottom flange where MPC varies from 0.52-0.92 for
the various tests, indicating a rather noisy mode. The evolution of the eigenfrequency values for each fiber as well their 95% confidence interval are shown in Figure 12. Bending modes 2 and 3 show a reduction in the eigenfrequency values, especially for the tests of the 6th cycle (tests 6a and 6b), which is in agreement with the results obtained from the accelerometer data (Figure 10). In Table 3, the average eigenfrequency values for each loading cycle are presented. The average values are calculated between the results of the tests that correspond to the top and the bottom fiber of this step. The percentile reduction of the eigenfrequency values is about 2% for the second and 3% for the third bending mode when the damaged and the undamaged condition are compared.

<table>
<thead>
<tr>
<th>Condition</th>
<th>1st Mode [Hz]</th>
<th>2nd Mode [Hz]</th>
<th>3rd Mode [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undamaged</td>
<td>72.25±0.54</td>
<td>173.01±0.40</td>
<td>317.17±0.20</td>
</tr>
<tr>
<td>Damaged</td>
<td>72.26±0.30</td>
<td>170.07±0.57</td>
<td>310.09±0.27</td>
</tr>
</tbody>
</table>

Table 3: Average eigenfrequencies with their 95% confidence interval between top and bottom fiber for the undamaged (tests 1a and 1b) and the damaged condition (tests 6a and 6b).

The eigenfrequency values have a good match with the ones obtained from the acceleration data, with the percentile differences to be less than 1% for all loading cycles. The range of the 95% confidence interval for the bottom flange fiber, as it is obtained from the SSI-cov, is wider than this of the top flange. However, that is expected when the raw strain data of the fibers’ sensors are compared. In Figure 13,
the Power Spectral Density (PSD) of two sensors, one from the top and one from the bottom fiber, are presented. Both sensors are located at the same location of beam’s longitudinal direction (Figure 7). The PSDs indicate a higher noise level in the bottom flange fiber, and consequently a lower Signal to Noise Ratio (SNR), as it can be easily seen in Figure 13, which results in lower identification accuracy and consequently to a larger confidence interval. The high noise level could be attributed to optical losses at the fiber’s connection.
The unit normalized modal strain shapes of the beam, as obtained from the SSI-cov and for the top flange fiber, are presented in Figures 14 and 15. A least-squares fit was also applied here for the determination of the scale factor $c$ that links the unit normalized mode shapes of the various tests with the unit normalized mode shapes of test 1a. To demonstrate the evolution of the modal strain shapes due to the imposed damage, combined graphs of the modal strain shapes that were identified in each loading cycle are presented. The modal strain shapes of the first two modes are only shown, as the strain level of the third mode was much lower than them (Figure 13 - peak at 300Hz), resulting to poor modal shape identification. The high noise level (or low SNR) existing in the strain data of the bottom fiber resulted in poor identification of the first bending mode. Therefore, only the evolution of the second modal strain shape is shown in Figure 15.

The modal strain shapes of the first mode (top fiber) do not pose any significant amplitude or shape changes which means that they did not manage to identify the damage that was introduced to the beam (Figure 14a). However in the modal strain shapes of the second mode, there are amplitude alterations and curvature changes for the tests of the last loading cycle (Tests 6a and 6b in Figures 14b and 15) where also a significant change in eigenfrequencies has been previously observed. Similar changes are also observed for test 5b for the bottom fiber, indicating that damage has been identified in an earlier step for this fiber. These alterations indicate that damage has been identified from the second modal strain shape. The damage is identified at the locations that it was observed during the experiment, in
the zones between the supports and the point of load application, where the shear force induced shear cracks during the progressive damage test (Figure 4). The results are also in agreement with the ones obtained from the accelerometer data modal analysis, where the damage has been also identified at the same locations.

6. CONCLUSIONS

This paper focuses on the experimental modal analysis of a pre-stressed concrete beam. FBG sub-microstrain data, processed with a peak-shift algorithm, and accelerometer data were used for the identification of the beam’s modal characteristics. The first three bending modes of the beam were successfully identified from both analyses. Furthermore, the damage induced in the beam through the progressive damage test was successfully identified.

The eigenfrequency values of the second and third mode were progressively reduced in every loading cycle, indicating reduction of stiffness and consequently damage. The mode shape of the third mode and the modal strain shape of the second mode were showing clear changes in curvature and amplitude, indicating the presence of damage. The locations at which these changes were identified, coincide with the locations where the damage was observed during the experiment.

The accuracy in the identification of damage from the FBG strain data processed with the FPC peak-shift algorithm is at least of the same magnitude with the accuracy obtained from the conventional accelerometer data. Therefore, the FBG strain sensors can serve as a valuable and accurate alternative choice for the vibration-based structural health monitoring while they provide with extra useful information, i.e. for locating early stage damage in structures.

REFERENCES


