Micro-deformation measurement on the concrete roadway surface slabs using Fiber Bragg Grating and analysis by computational simulation

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Abstract. This work shows a non-invasive method for micro-deformation measurements on concrete structures using Bragg grating sensors in optical fibers adhered to the surface. We present the measurements on roadway slabs under a load of 10 kN, and we find an approximated ratio of 2:1 between the deformation registered by the sensors and the values from a computational simulation with the finite element method. We propose the use of these sensors for structural monitoring of the slabs and this installation shape for avoiding bends that can damage the edges in the optical fiber in embebed sensors in vertical shape.

1. Introduction

The concrete roadway is not commonly used, because the asphaltic roadway is cheaper and its construction is easy. The concrete has lower deterioration and great mechanical resistance; however the overload caused by vehicular traffic produces micro-deformations in the surface that in some cases is enough for beginning the cracks. Nowadays, the control and monitoring systems are used for knowing in-situ and in real time de roadway state. Recently, the fibre optics sensor technology has been implemented in health monitoring systems on civil structures, such as the concrete roadway, because the fibre optics sensors are easily multiplexed and their materials are non-reactive with the material of the concrete [1]. These systems have been implemented with strain sensors embebed in the roadway [2], displacement sensors installed in the joints [2] and the temperature sensors to evaluate the effects on the structure by the environmental change, furthermore, this technology has been used in the characterization of the materials for constructions in tests of laboratory [3].

The concrete roadway is highly damaged due vertical strain produced by overload traffic [4]. This vertical strain can be measured using embebed fibre optics sensor in vertical position. The vertical position can produce breaks in the edge of the sensors because the fibre optics is very sensitive to damage due to bended and should be carefully installed inside the structure [5]-[8]. We present, a non-invasive method for measuring the vertical strain using Fibre Bragg Grating (FBG) that was attached on the surface concrete slab of the roadway. The reference values were calculated using the results of analysis of deformations using finite element method (FEM) to calculate the vertical strain close to the

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corner and close to the edge. Based on the results of the FEM, and the deformation measured by FBG sensor is determined the relation between both values. For future works, we propose to analyze different sensor sizes for improving the sensitivity for the smaller strain values, and to analyse the performance with high load.

2. Fiber Bragg Grating as strain sensor

A FBG is a device made in an optical fibre to which is modified the core refraction index with a periodical modulation. The FBG is a spectral filter. When broadband light is inserted on the FBG some wavelengths are reflected at a specific wavelength called the Bragg wavelength according to the equation [6]:

$$\lambda_{Bragg} = 2n_{eff}\Lambda$$  (1).

The parameter $n_{eff}$ is the effective refractive index that can be externally affected by mechanical and thermal alterations. In isothermal conditions, the spectral change of $\lambda_{Bragg}$ due to mechanical effects is:

$$\Delta \lambda_{Bragg} = \lambda_{Bragg}(1 - p_e)\epsilon_x$$  (2),

where $\epsilon_x$ is the longitudinal unitary deformation on FBG and $p_e$ the elasto-optic coefficient for longitudinal deformations. To $\lambda_{Bragg} = 1550$ nm the sensitivity is $1.2$ pm/$\mu$e which shows the possibility of spectral tuning on the FBG by mechanical perturbations, which allows the use these devices as optical spectral sensors with high resolution.

3. Numerical Simulation using Finite Element method (EFM)

The concrete slabs of roadway are made with slabs that are supported by a ground called sub-stand. The slab materials has great compression resistance and flexion, however are very sensitive to high load, due the strain related with the kind, vehicle-weight, frequency, slab size, environmental conditions, and mechanical proprieties of the concrete and ground [9].

Westergaard and Boussinesq equations are analytical models that have been proposed for modelling the deformations caused by vehicular weight upon the slabs [10]. Other models have been developed taking into account the multiples slabs that interacting on function of their proprieties [10]. However, numerical simulations have shown to be the most important method because allow to include constitutive equation and physical and geometrics characteristics of the physical systems. The most important numerical method is called Finite Element Method (FEM) which is a process of divisions in multiples sub-domains [11]. We can calculate with FEM the solutions of the equilibrium structural problem (see equation (3) and (4)), between applied load “f” and internal effort “σ” that produce unitary strain “ε” depending of constitutive proprieties of materials “C” according with:

$$\nabla \cdot \sigma + f = 0$$  (3),

$$\sigma = C\epsilon$$  (4).

We simulate the strain distribution by FEM, on a concrete slab of 3.5 m x 3.6 m x 0.25 m when is loaded with 10 kN-weight. The concrete slab-stand is of 0.50 m-thickness and is supported by a ground called sub-stand. The corners are located to 0.50 m of the slab edge for allowing the free transmission of the load. The sub-stand, is an elastic edge underneath stand such as is showed in the Figure 1. The simulation was made considering a uniform load distribution, edge conditions, interaction of the concrete slab with the stand and interaction of the stand with the sub-stand. The load application zones are rectangular of 10 cm x 7.0 cm that is almost the same that the contacts area
between wheels and concrete surface. The load applied over the slab is 10 kN (typical vehicular load), and the half pressure is ~250 kPa per wheel considering a uniform load distribution.

![Figure 1. Concrete slabs model. In the concrete slab was applied 10 kN-load above the rectangle zones that is approximately the wheel contact zone.](image)

The Table 1 shows the elastic proprieties of the slab, stand and sub-stand used in the experimental setup.

|                | Elastic Module | Poisson Ratio | Density   |
|----------------|----------------|---------------|-----------|
| Concrete Slab  | 27000 MPa      | 0.18          | 2300 kg/m³ |
| Stand          | 22000 MPa      | 0.20          | 2100 kg/m³ |
| Sub-Stand      | 180 MPa        | 0.35          | 1500 kg/m³ |

The simulation was made using 8779 elements with non-linear capacity response. The concrete slab was divided with tetrahedric elements (Solid 187) and the stand with hexahedric elements (Solid 186). The contact elements (Target170, Conta174) were used for modelling the non-linear interaction between the slab concrete and the stand. However, it was considered a structural static analysis in accordance with an elastic-linear model due to the load being lowest.

The Figure 2 shows the results of numerical system solution where it is observed a contour distribution that are the vertical displacements in µm. Close to the corner is ~3.7 µm and close to the edge side is ~2.8 µm approximately.
4. Experimental Setup
The figure 3 shows the experimental setup with FBG strain sensors of 10 cm, and a temperature sensor, both adhered in the concrete slab. The strain sensor 1 (SS1) is installed 10 cm-transversal edge and 50 cm-longitudinal edge, and the second one, the strain sensor 2 (SS2) to 50 cm-transversal edge and 180 cm-longitudinal edge. The strain sensors were adhered to concrete slab using a thin epoxy resin. The FBG sensors are sensitive to 4000 µε and the Interrogator of the Fiber Bragg Grating (BraggMeter FS4200) has a resolution of ~1 µε. The temperature sensor based on FBG was used as a reference for the measurement of the FBG strain sensors. The concrete slab was loaded by a vehicle of 10 kN-weight. The vehicle runs at low speed and stopped above the strain sensors. The sensors were connected to BraggMeter FS4200 Interrogator with a sampling of 200Hz.

5. Results
The Figure 4 shows the sensors response when the concrete slab loaded with 10 kN-weight, as well as the temperature sensor response. The initial values of the strain sensors were of 70 µε and the sensors behaviour on the time are observed when the wheels are above the sensors. The reference temperature
sensor does not change around 40 °C. In the Figure 4 are observed small changes in the regular values of the measurements due to irregular contact between the wheels and the sensors that produce changes pressure during the movement of the vehicle, it means, high pressure values in a short time. The deformations were 64.3 µε for SS1 and 47.6 µε for SS2. The sensors length are 10 cm, consequently the displacement are approximately 6.4 µm in SS1 and 4.8 µm in SS2.

Figure 4. a and b show the sensor response for a load of 10 kN due at vehicle. The deformations are approximately for SS1: 64.3 µε, and SS2: 47.6 µε. The sensor length is 10 cm, consequently the displacements are SS1: 6.43 µm, and SS2: 4.76 µm.

The FBG sensors are made for measuring the longitudinal strain. In this experiment, we show how to relate the longitudinal strains with the vertical deformations in a concrete slab surface, as was presented in the Figure 5. Given the bend induced on the sensor by the application of the pressure, that in good approach can be visualized like a symmetric displacement in the ends of application of the pressure, then, the deformation measured by the sensor corresponds at the double of the deformation vertical that generated the wheel on the surface. Under this criterion, the vertical displacements in the sensors zones will be the half of the registered by the sensors. The values are 3.2 µm, for the zone where the SS1 is located and 2.4 µm on the SS2. Comparing these values with the numerical simulation, which are a ideal reference, with values of 3.7 µm and 2.8 µm, respectively, then, in this experiment we obtained a relative error lower to the 15%.

Figure 5. Visualization of a 6000x-zoom by FEM that represents the results of the surface deformation
6. Conclusions
We show a new method to measure vertical deformation in a concrete slab with FBG sensors of 10 cm, adhered to the surface, and the relation of these measures with the results obtained by EFM. In this test, the relation was 1:2 between the vertical deformations obtained by the MEF and the deformations registered by the FBG sensors. For future works, we will propose determine the relations of different size sensors, like a possible alternative to increase the sensitivity and to improve of measurement, in addition to verify if the relation obtained in this work is the same with vehicular load higher than 10 kN or when the vehicle runs to high speed. This method is a good alternative for measuring of vertical deformation upon concrete slabs without invasion of the structure that would allow the experimental identification of overloads that cause a progressive deterioration of the slab, furthermore, is a good method for the identification of the superficial damages and cracks, and the early determination of zones of fractures by means tests using these FBG sensors.

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